

# BIOLOGY

CLASS XII  
PART I



# B I O L O G Y

## *A Textbook for Senior Secondary Schools*

CLASS XII

PART I

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**Front Cover:** The ground shows a magnified picture of nerve cells in the human brain. On this appears a sectional view of the brain — perhaps, the most complex organ in an animal — which is contrasted with the picture of a flower — a comparatively simpler part of a plant.

**TRANSPARENCIES**

*Courtesy:* Prof. Veena Bijlani  
Prof. H.Y. Mohan Ram

**Back Cover:** The ground is a magnified view of nerve cells in the brain of a rat. On this is shown film strips of a developing rat-fetus.

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## FOREWORD

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TODAY, biology as a discipline of science has pervaded every walk of life. It is an indispensable area of human knowledge for the physical, social and mental well-being and the scientific and technological growth. So the urgency of bringing about qualitative changes in biology education as an integral part of science at all school stages had been stressed in the National Policy on Education (1986). Students opting for biology as a subject of study at the senior secondary stage need to be prepared adequately for the academic and professional courses at the tertiary level of education, and those who drop out after the senior secondary stage and enter the world of work need to be more equipped to meet the challenges of life. To achieve these dual objectives, the present textbook in biology for Class XII has been developed by the Biology Textbooks Development Committee in continuity with the textbook for Class XI published by the NCERT in 1988.

In 1986 the NCERT set up an Advisory Committee under the chairmanship of Prof. C.N.R. Rao, Director, Indian Institute of Science, Bangalore, to develop instructional packages in science and mathematics from the upper primary to the senior secondary school stage. Under the chairmanship of Prof. H.Y. Mohan Ram, Department of Botany, University of Delhi, a Biology Textbooks Development Committee was constituted to produce an instructional package for senior secondary schools. The Committee consisted of eminent scientists from leading research institutions, outstanding teachers from universities, biology educationists including the senior faculty members of the Department of Education in Science and Mathematics (DESM), NCERT, and practising teachers.

My appreciation and thanks are due to Prof. H.Y. Mohan Ram, Chairman, and all the members of the Committee for their sustained efforts to bring out this volume. I am indebted to all the participants of the two National Review Workshops for their commendable contribution towards the finalisation of the manuscript of this textbook.

I would like to record my thanks to Prof. B. Ganguly, Head, DESM, NCERT, for making available to the Committee all facilities for holding the meetings at Bangalore, Lucknow and Delhi. My thanks are also due to Shri C.N. Rao, Head, Publication Department, NCERT, Shri D.P. Gupta, Editor, Publication Department, NCERT, and the publication team for quality production of this textbook.

Lastly, I would like to record my appreciation to Prof. J. Mitra, Coordinator of the Committee, for his constant and unstinted help to the publication team in designing the textbook and for seeing it through the press.

Suggestions for further improvement of the textbook will be most welcome.

**P.L. MALHOTRA**  
*Director*  
National Council of  
Educational Research and Training

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## PREFACE

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THE textbook in biology for Class XII is an outcome of the continuation of efforts to implement the National Policy on Education (1986). Part I contains two units—'Multicellularity in Plants : Angiosperms' and 'Multicellularity in Animals'—covering Unit Five and Unit Six of the syllabus, respectively. Plants, fungi and animals have attained an organisational level in which cells have undergone differentiation and specialisation to develop into 'cellular cooperatives' with a marked division of labour. The cells constituting tissues and the tissues constituting organs function with a remarkable harmony, in spite of retaining their individuality. Thus, multicellularity marks a new milestone in the evolutionary history of organisms. The diverse structures and the varied functions of the Kingdom Plantae as depicted by angiosperms have been dealt with in Unit Five. There are two reasons for selecting angiosperms: they are the most highly evolved among the land plants and they constitute the major resource base for human needs. An account of morphology, anatomy and physiology as exemplified by representative phyla in the Kingdom Animalia is given in Unit Six.

A tremendous explosion of knowledge has occurred in biological sciences during the last four decades. Consequently it has become necessary to introduce several new concepts even at the secondary school level without sacrificing the basic aspects.

This textbook has been written by several authors. Therefore the styles of presentation of the text vary. Nevertheless, the interdisciplinary nature of biology has been emphasised and the linkages among the fundamental concepts of biology have been established.

It is hoped that the textbook will stimulate in students the spirit of inquiry, the power of critical observation and the ability to understand facts and perceive broad biological concepts. Each unit begins with an overview of the contents dealt with in the chapters. A summary is given at the end of every chapter.

In preparing this book clarity has been given preference over brevity. Most students should be able to learn the contents by themselves. The text is profusely illustrated. Several boxes containing additional information have been included to motivate students to take a lively interest in the subject. All these have understandably increased the size of the book.

*The matter within the boxes does not form the course content. It is not meant for classroom teaching and should not be used by teachers for setting questions for the Board examination.*

I thank Dr P. L. Malhotra, Director, NCERT, for his deep interest and sustained support at all stages of the preparation of this textbook and Prof. C. N. R. Rao, Director, Indian Institute of Science, Bangalore, for persuading me and other members of Biology Textbooks Development Committee to take up this important, yet challenging, task.

In the preparation of Unit Five, the following persons critically reviewed the drafts of the chapters mentioned against their names and offered valuable suggestions : Prof. Salil Bose, Jawaharlal Nehru University, New Delhi, Dr K. V. Sane, Director, National Botanical Institute, Lucknow, Dr Gita Mathur, Gargi College, New Delhi (Chapter 29), Dr K.R. Shivanna and Smt. Subhadra Menon, Department of Botany, University of Delhi (Chapter 30), Dr Lakshmi Devi and Dr S. Mahadevan (Chapters 29 and 31).

I am indebted to Dr S. Adhikari (Presidency College, Calcutta), Dr Bharati Sarkar and Prof. B. Ganguly for reviewing the entire manuscript of Unit Six. Dr S. Chatterjee, Jawaharlal Nehru University, New Delhi, and Dr U. Malik, NCERT, New Delhi, critically went through Chapter 41 and Chapter 32, respectively, and made valuable suggestions.

Deep appreciation is extended to Prof. B. Ganguly, Head, Department of Education in Science and Mathematics, NCERT, New Delhi, for his total involvement and cooperation in bringing out this work.

Many persons have rendered ready help in several ways. Lack of space does not permit me to thank each of them individually. Nevertheless, I shall be failing in my duty if I did not acknowledge the enormous support and assistance received from Dr B. Hari Gopal, Dr Manasi Ram and Smt. G.S. Sundari Iyer throughout this endeavour.

It has been a pleasure working with the members of the Committee and the authors, who are talented, totally dedicated, objective and critical in their views and cooperative. I gratefully thank all of them for their friendly spirit, labour and trust.

Appreciation is extended to Dr M.N.B. Nair, Shri S.K. Mazumdar, Smt. Chandana Bhattacharya and Dr B. Hari Gopal for preparing neat drawings and photographs.

This has been an uphill task. Constraint of time has prevented the formative evaluation of the chapters. However, suggestions for improvement are welcome from teachers, subject experts and students.

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Delhi

H.Y. MOHAN RAM  
Chairman  
Biology Textbooks  
Development Committee

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### **Class XII**

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## ACKNOWLEDGEMENTS

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The members of the Biology Textbooks Development Committee considered it valuable to discuss the draft chapters with subject experts for technical accuracy of the contents and with teachers who have to use the textbook in teaching-learning situation in schools. To elicit their critical views and constructive suggestions, two National Review Workshops were held from 21 to 25 September 1987 (for the chapters under Unit Five) and from 14 to 17 November 1988 (for the chapters under Unit Six), respectively, at the National Council of Educational Research and Training, New Delhi. Several changes have been incorporated in the manuscript as a result of interaction.

The following participated in the National Review Workshops.

*National Review Workshop (21 to 25 September 1987)*

Prof. R.N. Kapil, Department of Botany, University of Delhi; Prof. Manohar Lal, Department of Botany, University of Delhi; Dr D. Kulhara, Professor of Botany, State Institute of Science Education, Jabalpur (M.P.); Smt. Inder Mohini Chugh, P.G.T. (Biology), Govt. Girls Senior Secondary School, Andrews Ganj, New Delhi; Dr G Rajendrudu, Lecturer in Botany, Sri Venkateswara University, Tirupati; Shri S.P. Sexena, Jr. Science Counsellor, State Council of Educational Research and Training, New Delhi; Shri J.S. Mavlanker, Asstt. Teacher. Sheth N.T.M. High School, Surendranagar, Gujarat; Shri Suresh Chandra Sharma, P.G.T. (Biology), Govt. Boys Senior Secondary School, Sector VI, R.K.Puram, New Delhi; Smt. Vasantha Padmanabhan, P.G.T. (Biology), Kendriya Vidyalaya, F.R.I., Dehradun (U.P.); Shri S. D. Rukmangad, Lecturer, State Council of Educational Research and Training, Jahangirabad, Bhopal (M.P.); Smt. S.P. Sharma, P.G.T. (Biology), Kendriya Vidyalaya, JNU Campus, New Delhi; Ms. Lata Khanna, P.G.T. (Biology), Kendriya Vidyalaya, Lawrence Road, Delhi; Shri Damodar Tewari, P.G.T. (Biology), Govt. Boys Senior Secondary School, Netaji Nagar, New Delhi; Smt Sushma Misri, Research Officer in Zoology, State Institute of Education, Jammu, J & K State; Shri Ab. Hamid Teli. Lecturer in Botany

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*National Review Workshop (14 to 17 November 1988)*

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I have pleasure in thanking them for their generous help in this national effort.

The Committee is indebted to many other teachers and subject experts for their counsel.

On behalf of the Committee I extend my thanks to Dr R.S. Thakur, Director, Central Institute of Medicinal and Aromatic Plants, Lucknow, for providing the venue for holding a meeting of the authors.

H.Y. MOHAN RAM  
Chairman  
Biology Textbooks  
Development Committee



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## PHOTOGRAPHS

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- Page 394*    Cotton boll  
(*Photograph:* Prof. H.Y. Mohan Ram)
- Page 432*    Apple Crop  
(*Photograph:* Prof. H.Y. Mohan Ram)
- Page 442*    Gazania in bloom  
(*Photograph:* Prof. H.Y. Mohan Ram)
- Page 480*    Flowers — the reproductive structures of angiosperms  
(*Photograph:* Prof. H.Y. Mohan Ram)
- Page 506*    Yellow Maple  
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- Page 532*    Capillaries carrying blood to tissues  
(*Courtesy:* Biology Laboratory, DESM, NCERT)
- Page 590*    Respiratory system in man  
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(*Courtesy:* Biology Laboratory, DESM, NCERT)
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- Page 708*    Cellular structure of a rat's testis  
(*Courtesy:* Prof. P.K. Paul & Dr Neera Saxena, Dept. of Zoology, University of Delhi)
- Page 726*    Foetuses of a rat showing alizarin stained ossified tissues  
(*Courtesy:* Dr A.N. Bhisey & Dr M.G. Deo, Research Director, Cancer Research Institute, Bombay)

These photographs are not referred to in the text.

## GANDHIJIS TALISMAN

"I will give you a talisman. Whenever you are in doubt or when the self becomes too much with you, apply the following test :

Recall the face of the poorest and the weakest man whom you may have seen and ask yourself if the step you contemplate is going to be of any use to him. Will he gain anything by it ? Will it restore him to a control over his own life and destiny ? In other words, will it lead to Swaraj for the hungry and spiritually starving millions ?

Then you will find your doubts and your self melting away."

*M.K. Gandhi*

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### Teachers and Students!

You will find a large number of boxes in the text, each bounded on four sides by thick black lines (see for example page 112). The matter presented in the boxes is not meant for classroom teaching or for setting questions by the teachers for the Board examination. The purpose of providing additional information in the boxes is to arouse curiosity among students.

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## UNIT FIVE

### ***Multicellularity in Plants***

#### ***Angiosperms***

ANGIOSPERMS are the most highly evolved among plants. They show a wide diversity of size and form, from the dot-like duckweeds to the gigantic eucalypti. In contrast to the compact body of animals, plants generally have an enormous surface. This enables them to glean inorganic substances from the atmosphere and soil in extremely dilute concentrations and synthesise complex molecules with the help of the energy derived from the sun. Even large trees are built on a fairly simple modular pattern. They continually produce new tissues and organs by means of actively dividing cells in the meristems. Plants lack central control and supply systems (nervous system, circulatory system, lymphatic system, skeletal system etc.). Yet, they present a high degree of organisation and demonstrate a harmony of structure and function. A well-coordinated division of labour exists in the tissues of the root to absorb and conduct water and minerals and in the shoot to synthesise, translocate, store and mobilise complex organic substances.

Plants are anchored in the soil and cannot move away from stresses. They face stresses entirely through physiological adaptations and growth responses.

Flower is a condensed shoot modified to effect sexual reproduction. Presence of ovary and double fertilisation are unique to angiosperms. Seeds and fruits serve as packets of dispersal. Seeds contain embryos in a state of suspended animation and are often stocked with plentiful reserve food. They can tide over unfavourable conditions and germinate when the environment is conducive. Besides sexual reproduction, plants exhibit vegetative propagation. These reproductive strategies have been responsible for the success of angiosperms as land plants. It is possible to clone useful plants through conventional and tissue culture methods, as well as to join plants by various types of grafting.

Most annual and biennial plants culminate their life cycle after flowering and fruiting. In perennials, seasonal production of fruits does not result in death. They continue to live for many years.

Plant growth and development involve a complex series of morphological, anatomical and biochemical events. How these events are controlled is a mystery.

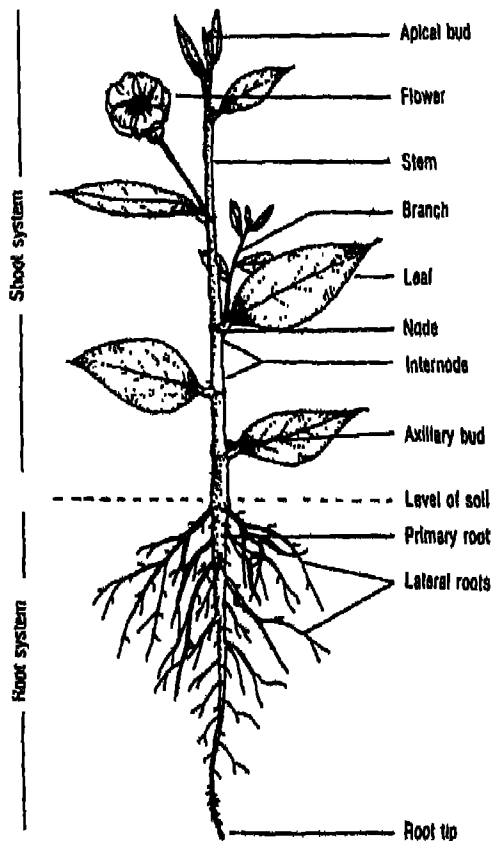
Nevertheless, it is recognised that internal and environmental factors influence development. It is not fully known what factors trigger flowering in plants. However, daily duration of light/darkness and temperature are known to induce flowering in some classes of plants. Certain plant growth regulators have been identified which cause specific effects. How exactly these function is not known. Thus, the study of the life of flowering plants is full of challenges and opportunities.



## MORPHOLOGY AND ANATOMY OF FLOWERING PLANTS

### MORPHOLOGY

THOUSANDS of angiosperms exhibiting a wide spectrum of forms and occupying numerous habitats occur on the earth. Just as a person is recognised by his external features such as height, complexion, shape of the nose, eye colour, and texture of the hair, so are plants identified by their morphology. It is virtually impossible to know all the flowering plants even for a professional taxonomist. However, a student of biology must understand the basic architecture of plants to be able to recognise, describe and classify them. Flowering plants consist of an axis with an underground root system and an aerial shoot system (Fig. 26.1). The shoot has a stem and a system of branches and leaves. The root and the shoot constitute the vegetative part of the plant body. The flower, the fruit and the seed comprise the reproductive structures. One of the fascinating aspects of biology is to understand the meaning of diversity of form and its probable relation to functions. More importantly a biologist is deeply interested



in the evolutionary and adaptive significance of plant form.

### Root

The embryo enclosed within the seed consists of two parts—the radicle which gives rise to the root and the plumule which is the progenitor of the shoot. In nearly all dicotyledonous plants the PRIMARY ROOT is a direct prolongation of the radicle. It

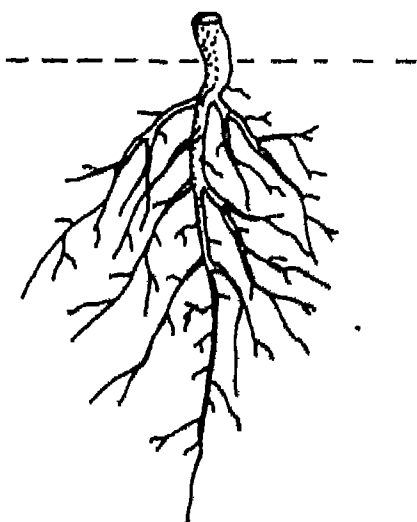


Fig. 26.2 Tap root system

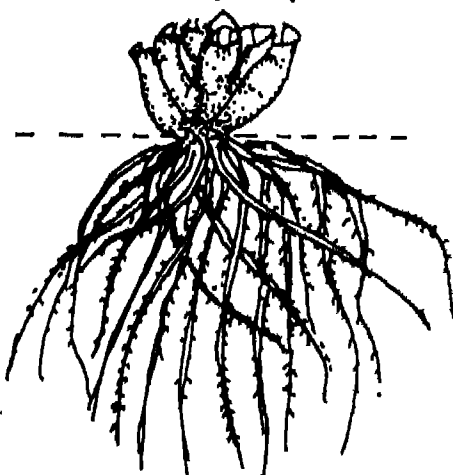


Fig. 26.3 Fibrous root system

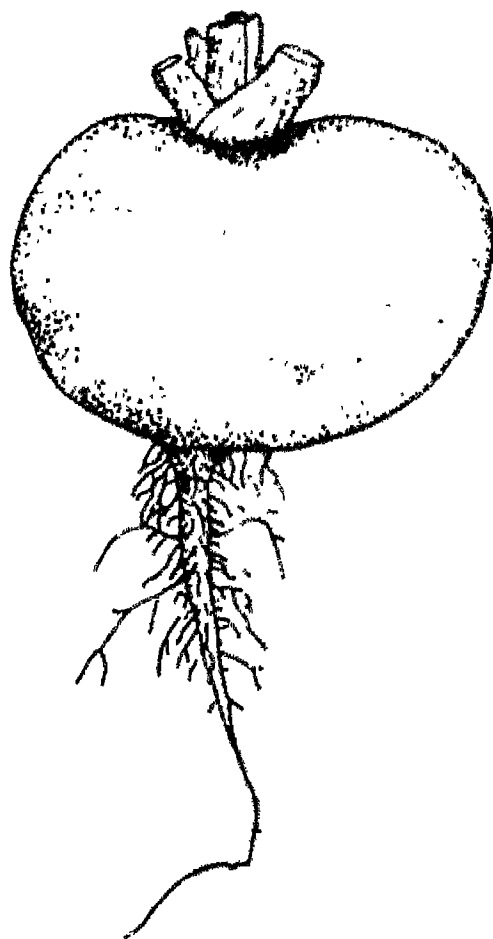


Fig. 26.4 Napiform root of turnip

remains distinct and bears lateral roots of several orders throughout the life of the plant. The primary root along with its branches is termed the **TAP ROOT SYSTEM** (Fig. 26.2). A **FIBROUS ROOT SYSTEM** may arise due to repeated branching of the radicle (Fig. 26.3). When roots arise in any place other than the root system, such as on stems, they are called **ADVENTITIOUS ROOTS** (Fig. 26.12). Typical examples of plants bearing adventitious roots are grasses, the banyan tree and mangroves. The main functions of the root system



are to anchor the plant to the soil and to absorb water and nutrients. Since these two functions are not critical for floating or submerged-aquatics, the root system may be poorly developed or totally absent in them (e.g. *Myriophyllum*, *Ceratophyllum*, *Utricularia*). Roots may be modified to perform functions other than those mentioned above, such as storage, assimilation and additional support.

#### Modifications of Tap Roots

In some plants, tap roots are modified for storing reserve materials. These roots are usually swollen and assume various forms. A swollen root tapering at both ends is termed FUSIFORM, (e.g. radish). When the root is globular and tapers

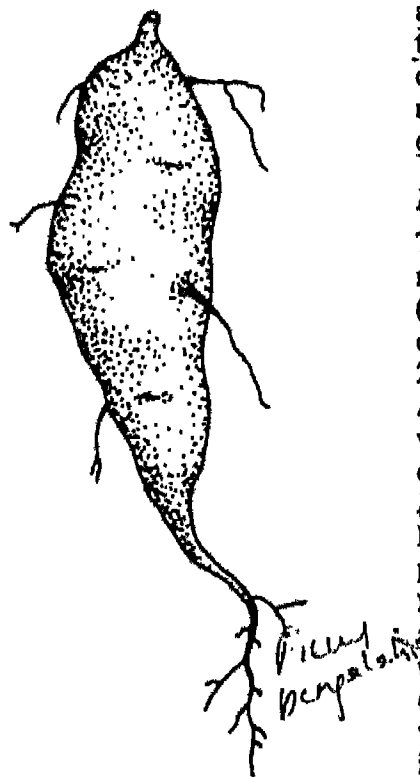


Fig. 26.5 Tuberous root of sweet potato

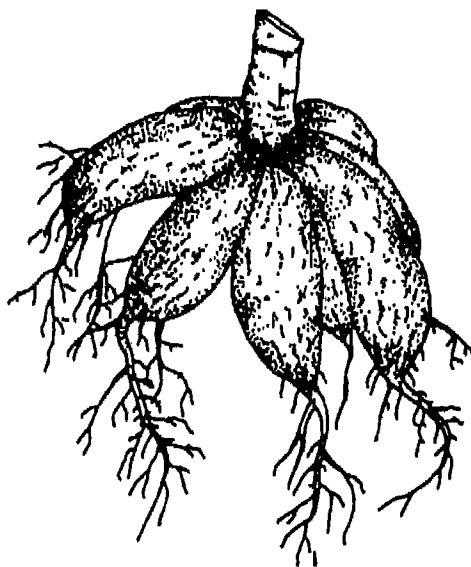


Fig. 26.6 Fasciculated roots of *Dahlia*

abruptly as in turnip and beet root, it is termed NAPIFORM (Fig. 26.4). The shape of the carrot root is CONICAL, whereas the root of *Mirabilis* (4' O clock plant) with no definite shape is termed TUBEROUS.

#### Kinds of Adventitious Roots

The sweet potato has TUBEROUS storage roots of various shapes that occur singly (Fig. 26.5). When storage roots occur in clusters as in *Asparagus* and *Dahlia* (Fig. 26.6) they are called FASCICULATED. Adventitious roots are called BEADED when they have swollen regions at frequent intervals as in *Portulaca* and *Momordica charantia* (bitter gourd). Roots that provide additional support to plants are broadly of two types. PROP ROOTS are massive, pillar-like structures as those in a banyan tree. They start as tiny outgrowths from aerial branches but extend downward, becoming large and woody. On reaching the soil they develop into columns and allow the tree canopy to extend over a large area (Fig. 26.7).

Clusters of roots which grow downward



Fig. 26.7 Prop roots of a banyan tree (The great banyan tree of Calcutta) (Photo: H.Y. Mohan Ram)

from the base of plants such as maize, sugarcane and screw pine (Pandanus) are termed STILT ROOTS. In some plants such as Tinospora and Trapa, adventitious roots develop chlorophyll and photosynthesise. They are called ASSIMILATORY ROOTS. Cuscuta and other parasitic plants develop roots which penetrate the host-tissue and obtain nutrition. They are called HAUSTORIA.

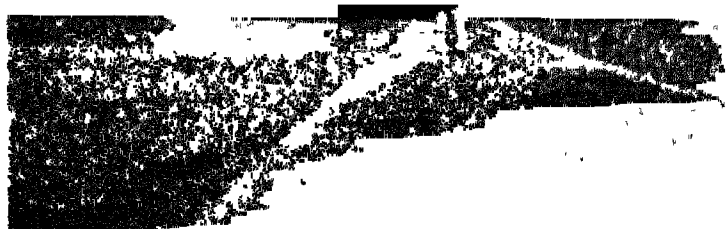
### Stem

The stem arises from the plumule and bears leaves, branches and flowers (Fig. 26.1). It is generally erect, strong and usually grows away from the soil (negatively geotropic). There are also several plants in which the stem is weak and it either trails on the ground or twines around a support. Stems are differentiated into regions called NODES. Leaves and branches arise at nodes. The portion

between the nodes is called the INTER-NODE (Fig. 26.1). The growing apex of the stem is covered by numerous, tiny, developing leaves and is called the APICAL BUD. Buds also arise in the AXILS of leaves. They are termed AXILLARY or LATERAL BUDS. These buds give rise to branches or flowers.

Several classes of plants are recognised on the basis of the height and strength of the stem and their life-span. HERBS are small plants with a soft stem. Medium-sized plants with woody stems that branch profusely from the base and attain a bushy appearance are called SHRUBS. TREES have a stout and tall trunk with profuse branching. Plants which complete their life-cycle within one season are termed ANNUALS (rice, groundnut, sunflower). BIENNIALS complete their life-cycle in two seasons (e.g. radish, cabbage). Plants that usually survive for a number of years and produce

There are several large banyan trees (botanically called *Ficus bengalensis*) in India. The largest, popularly known as the great banyan tree, is located in the Indian Botanic Garden in Howrah. It is an object of wonder and admiration. It is more than 200 years old and its main trunk which was attacked by a fungus was removed in 1925. The girth of the main trunk was 32.49 m. The tree originally grew on a wild date palm before the establishment of the Garden. A large number of aerial roots are produced from its branches. The total number of such roots which have already reached the ground is about 1600. The circumference of its crown is over 404 m. Maximum height attained by one of its branches is 29 m. The tree is a star attraction to the visitors. There was such a rush by people to wander among its props that their treading had caused compaction of the soil, leading to water logging and suffocation. Apprehending that the tree may be damaged, the Garden authorities have got the soil raked and have put a barricade around the tree to protect it. Two other massive banyan trees are found in India. One is at Adayar in Madras and the other at Ketohalli, a village near Bangalore. Try to make a list of the largest, tallest and the most unusual trees in our country.



flowers and fruits during specific seasons are termed PERENNIALS (mango, lemon, apple, neem, coconut, date and bougainvillea).

### Diverse Forms of Stems

Besides bearing branches, leaves and flowers, stems perform other functions such as PERENNATION and vegetative propagation. Their forms become greatly changed to suit these additional functions.

Underground Stems: Stems of some plants remain in the ground and serve the function of perennation and storage of food. They produce aerial shoots annually. They resemble roots superficially but are distinguishable by the presence of scales<sup>(s)</sup> leaves and buds at nodes. Such stems also act as a means of vegetative propagation. Various names are given to modified stems on the basis of their form.

RHIZOMES occur in plants such as ginger (Fig. 26.8) and banana. They are prostrate and thickened stems that grow horizontally under the soil. Nodes are marked as dry scars. They bear scale leaves, with buds on branches in their axils. Rhizomes produce adventitious roots in profusion.

A BULB is characterised by the presence of a highly condensed and discoidal stem and a large number of fleshy scale leaves (Fig. 26.9). The terminal bud in the centre of the bulb gives rise to the aerial shoot, that subsequently bears flowers. A cluster of adventitious roots is noticed at the base of the bulb. Onion is a familiar example of a bulb. In garlic several bulblets (small bulbs or cloves) may be seen within a large bulb. These arise from axillary buds and are capable of developing into new plants.

CORM is the swollen base of an underground stem axis, enclosed by dry, scale-

like leaves (Fig. 26.10). It is found in a number of plants such as *Gладиолус*, *Амриphophallus*, *Собирасия* and *Алиссия*. It differs from a bulb in having a greater amount of stem tissue with distinct nodes and internodes.

A TUBER (Fig. 26.11) is a modified stem which develops underground by the swelling of the tip of a stem (stolon). It stores a large amount of reserve materials primarily starch. Potato is a typical example of a stem tuber. The 'eyes' that you see on its surface represent nodes, each consisting of one or more buds subtended by a leaf scar (which resembles an eye brow). The parent plant which bears numerous tubers dies at the end of the growing season. New plants arise from the tubers.

Sub aerial Stems In certain plants a few branches are weak, lie prostrate on the ground or may become buried in the top soil. Aerial branches and adventitious roots develop at the nodes. Independent plants may be obtained by detaching an entire branch or a node. Such plants are commonly known as CLIMBERS. Climbers are of different types. A creeping stem with long internodes, running horizontally on the surface of the soil is called a RUNNER (Fig. 26.12). Roots are given out at nodes. Axillary buds form new aerial shoots. Many grasses, *Гризис* and mint propagate by runners. A STICKER is like a runner but originates from the basal and underground portion of the main stem. It is shorter and stouter than a runner. It grows horizontally for a distance beneath the soil and then emerges obliquely, bearing a leafy shoot as in *Chrysanthemum*.

A STOLON is a slender lateral branch that arises from the base of the main axis. After growing aurally for sometime the branch arches downwards to touch the

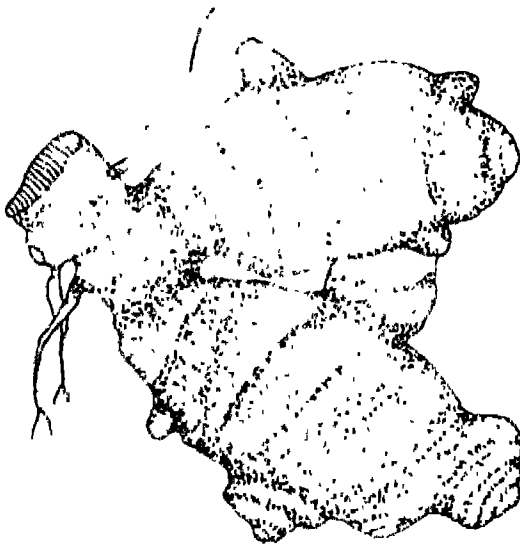


Fig. 26.8 Rhizome of ginger

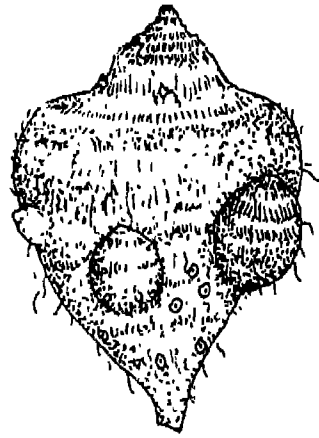
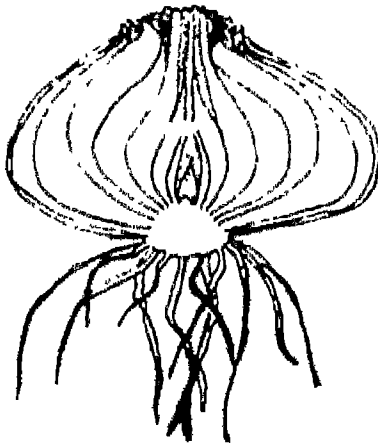
Fig. 26.10 Corm of *Colocasia*

Fig. 26.9 Vertical section of onion bulb

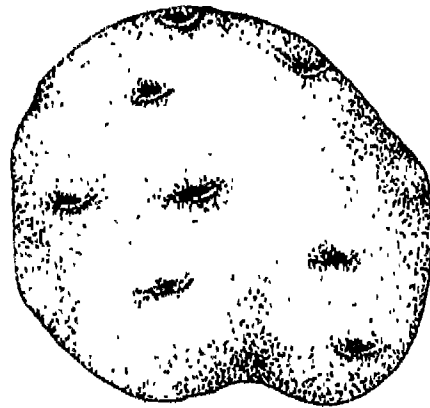


Fig. 26.11 Tuber of potato

ground, where its terminal bud gives rise to a new shoot and roots. Jasmine (*Jasminum*) is a common example of a stolon-bearing plant.

#### Special Modifications of Stems

Some stems perform unusual functions. Stem tendrils develop from axillary buds. They are slender and spirally coiled (spring-like) structures and help plants such as gourds (cucumber, pumpkin,

water melon, and other cucurbits), grape vine (*Vitis*) (Fig. 26.13) and passion flower (*Passiflora*) to climb.

When axillary buds develop into woody, straight and pointed structures they are called THORNS. Sometimes a thorn bears leaves also. Thorns are found in many plants such as *Citrus* and *Bougainvillea* (Fig. 26.14). They protect plants from browsing animals.

In cacti, euphorbias and a few other

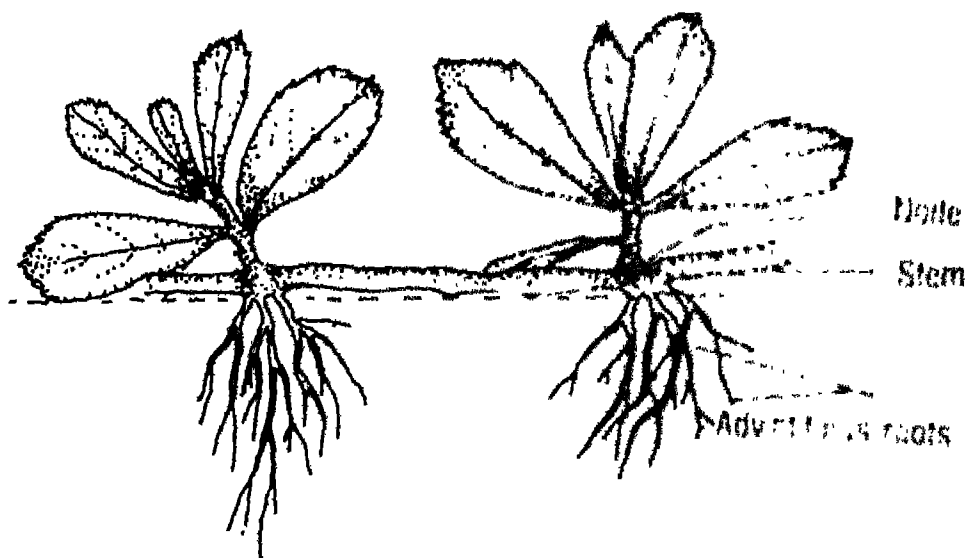


Fig. 26.12 A runner. Note the presence of a shoot and adventitious roots at each node



Fig. 26.13 Tendrils of grape vine  
(Photo: Dr. M.N.B.Nair)



Fig. 26.14 Axillary thorns of *Bougainvillea*

plants of the arid regions, stems are fleshy, cylindrical (*Casuarina*) or flattened (*Opuntia*). They contain chlorophyll and carry out photosynthesis. They are called PHYLLOCLADES and they have several nodes and internodes. Their true leaves are reduced to spines or scales. [A CLADODE is a phylloclade with one or two internodes only. It resembles a leaf. A cladode arises in the axil of a much reduced scale leaf (*Asparagus*, *Ruscus aculeatus*) (Fig. 26.15).

### Leaf

A leaf is a lateral, flattened structure borne at a node. It usually has a bud in its axil. Owing to the presence of chlorophyll, the leaf constitutes the main photosynthetic organ of the plants. Leaves initiate from the SHOOT MERISTEM as PRIMORDIA and gradually enlarge as they grow older.

A leaf consists of three parts, namely (i) lamina (ii) petiole, and (iii) leaf base (Fig. 26.16). In many monocotyledons the leaf base expands into a sheath that partially or wholly encircles the stem (Fig. 26.17). In several dicotyledonous plants the leaf base bears two lateral appendages called STIPULES. Stipules vary in form and size. In plants such as *Acacia* and *ber* (*Zizyphus*), the stipules are spiny. In many members of the bean family the base of the leaf is swollen and is termed PULVINUS (Fig. 26.18). A pulvinus is responsible for sleep movements.

The expanded and generally prominent portion of the leaf is called the LAMINA. It is traversed by a number of veins and veinlets. The prominent vein in the middle is known as the MIDRIB. Veins form the skeleton of the lamina (Fig. 26.19) and act as channels for the transport of food, water and minerals.

The shape of the lamina varies from

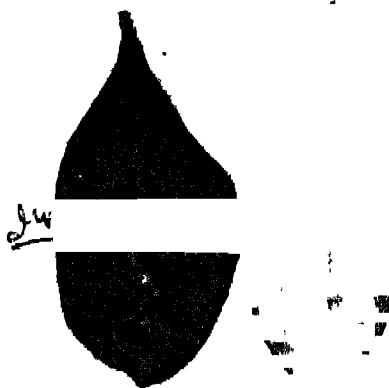


Fig. 26.15 Cladodes of *Ruscus aculeatus* bearing flowers (Photo: Dr. B. Harigopal)

plant to plant. The various shapes of lamina are shown in Fig. 26.20. The margin of the leaf may be even and smooth (termed ENTIRE) as in banyan, grasses and banana

Fig. 26.16 A shoot of *Ficus elastica* showing red, united stipules enclosing the leaf inside (Photo: H.Y. Mohan Ram)

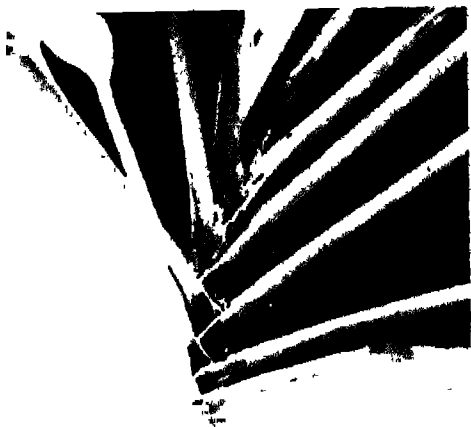


Fig. 26.17 Leaf sheaths of *Dracaena* (Photo: Dr. M.N.B. Nair)



Fig. 26.18 A branch of a leguminous plant showing pulvinus at the base of each compound leaf

or WAVY as in *Polyalthia* or notched like a saw (SERRATE) or lobed (Fig. 26.21). The tip of the leaf (APEX) has various shapes. A few common types are shown in Fig. 26.22.

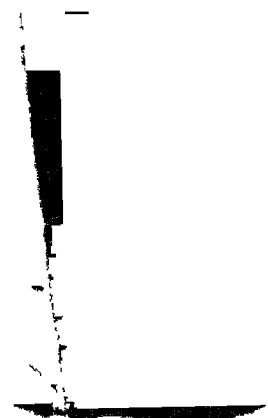


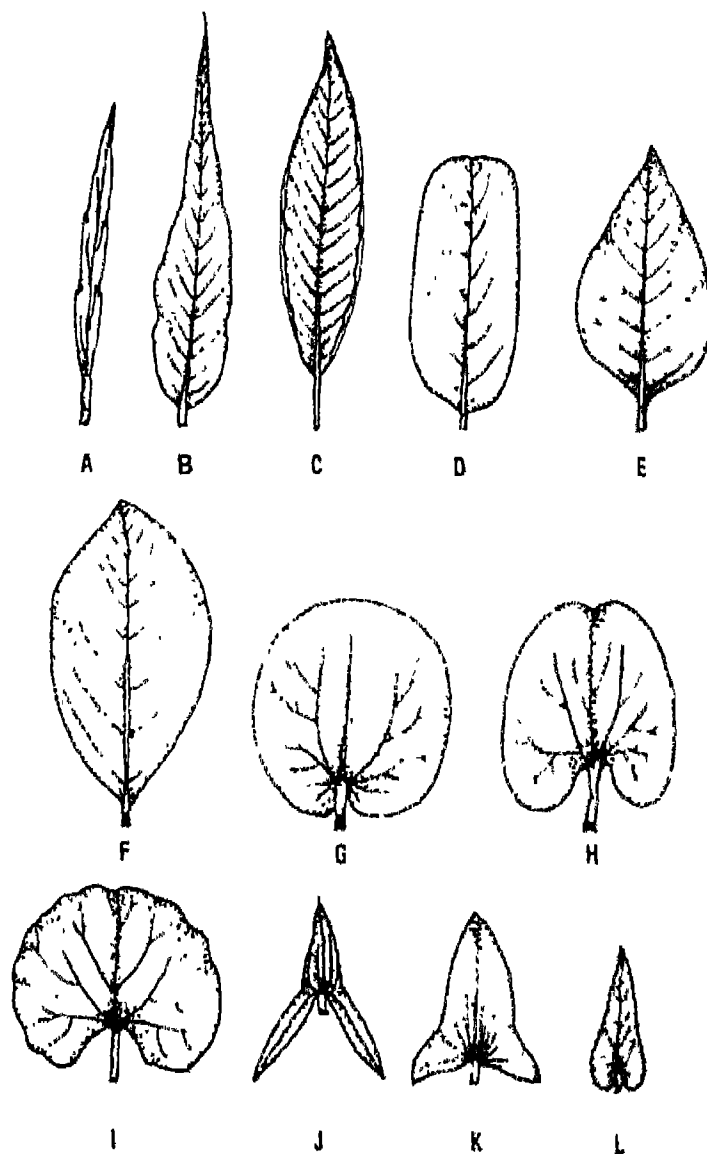
Fig. 26.19 A leaf of peepal showing a skeleton of veins (Photo: Dr. B. Harigopal)

The arrangement of veins in the lamina is termed VENATION. It is of two types: (i) reticulate and (ii) parallel. In the first type, veins are irregularly distributed to form a network (Fig. 26.23). It is a characteristic feature of the dicotyledons such as peepal and *Hibiscus*. In the second, the veins, running parallel to one another, do not form a network. Parallel venation is a characteristic feature of the monocotyledons such as lilies, banana, bamboos, other grasses and cereals (Fig. 26.23). There are a few exceptions to these two types of venation. Look for these in a garden.

#### *Simple and Compound Leaves*

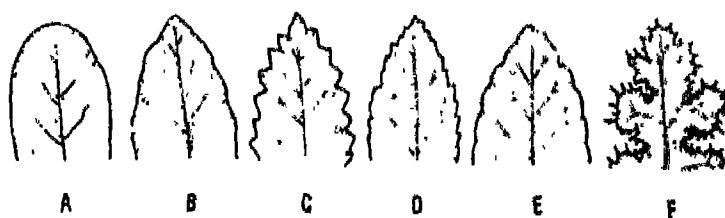
A leaf is said to be simple when its lamina is entire or is incised but the incisions do





**Fig. 26.20** Various lamina shapes

A. Linear; B. Lanceolate; C. Elliptic; D. Oblong; E. Ovate; F. Obovate; G. Orbicular; H. Cordate; I. Reniform; J. Sagittate; K. Hastate; L. Auricled



**Fig. 26.21** A few common types of leaf margin

A. Entire; B. Undulate; C. Dentate; D. Serrate; E. Crenate; F. Pinnately lobed

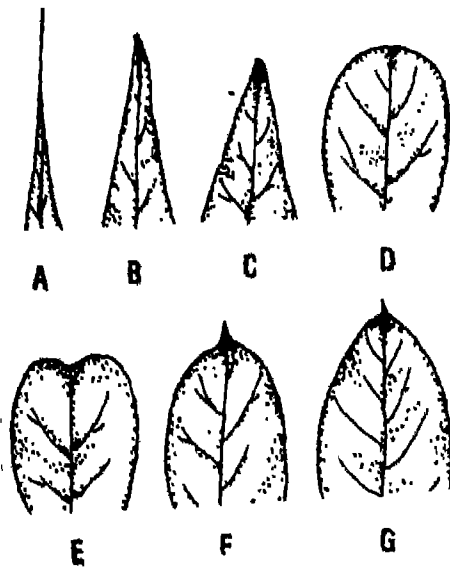


Fig. 26.22 Patterns of leaf tip

A. Acuminate; B. Acute; C. Obtuse;  
D. Truncate; E. Retuse; F. Cuspidate;  
G. Mucronate

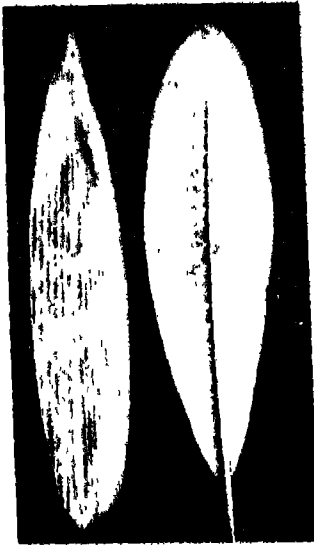


Fig. 26.23 The two main types of venation. Left, parallel; right, reticulate venation (Photo: Dr. M.N.B.Nair)

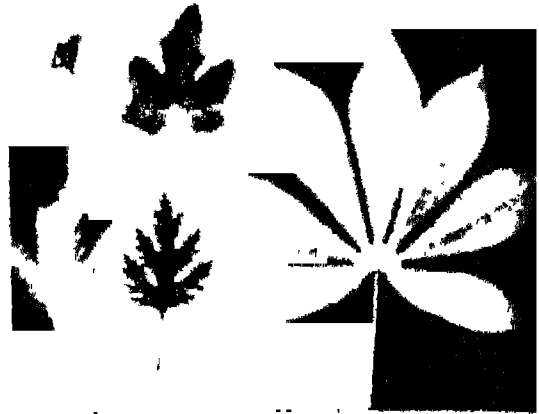


Fig. 26.24 Simple leaves with different degrees of incision of the lamina (Photo: Dr. M.N.B.Nair)

not touch the midrib (Fig. 26.24). When the incision of the lamina goes down to the midrib, the leaf becomes compound because it has a number of leaf segments. These leaf segments are known as **LEAFLETS**. A leaflet is like a simple leaf but it lacks a bud in its axil. Compound leaves may be of two types: (a) pinnate, and (b) palmate. A compound leaf is said to be pinnate when the leaflets are lateral to the midrib (**RACHIS**) (Fig. 26.25). In palmately compound leaves, the petiole bears a number of leaflets which resemble the fingers in our palm (Fig. 26.26). Depending upon the number of leaflets the leaves are called trifoliate (methi, fenugreek or *Trigonella*, clover or *Trifolium*), quadrifoliate (*Marattia*) and multifoliate (silk cotton or *Bombax*).

#### Phyllotaxy

The way in which leaves are arranged on a stem (**PHYLLOTAXY**) is an important diagnostic feature. When a single leaf arises at

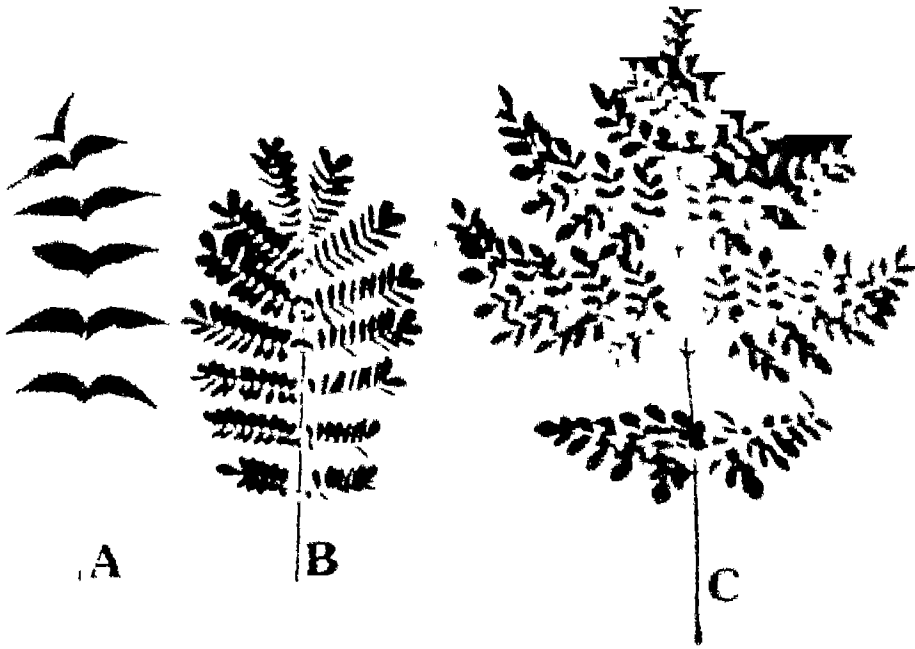


Fig. 26.25 Pinnately compound leaves

A. Unipinnate condition in neem. B. Bipinnate condition in '*neosalpinx*'. C. Tripinnate condition in *Moringa* (Photo: Dr. M.N.B. Nair)

a node, the phyllotaxy is said to be ALTER-NATE. Such leaves may arise in the same plane (Fig. 26.27A) or in a spiral fashion on the stem (Fig. 26.27B). The opposite arrangement is the one in which a pair of leaves are borne at a node opposite to each other (Fig. 26.27C). When three or more leaves occur at a node the pattern is termed WHORLED (Fig. 26.27D). Alternate leaves are found in mango and *Hibiscus*; opposite leaves are found in *mint* and *ak* (*Calotropis*) and whorled leaves occur in *oleander* (*Nerium*).

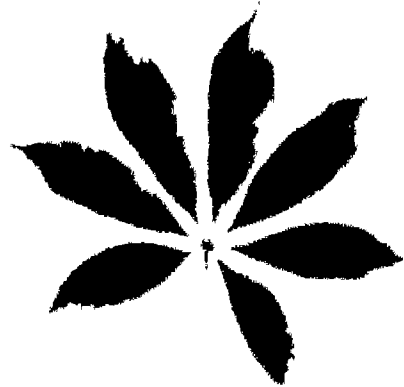


Fig. 26.26 Palmately compound leaf of *Bambusa*

#### Leaves with Different Functions

Leaves are often modified to perform functions other than photosynthesis. They are converted into TENDRILS for climbing as in *pea*, or into SPINES for

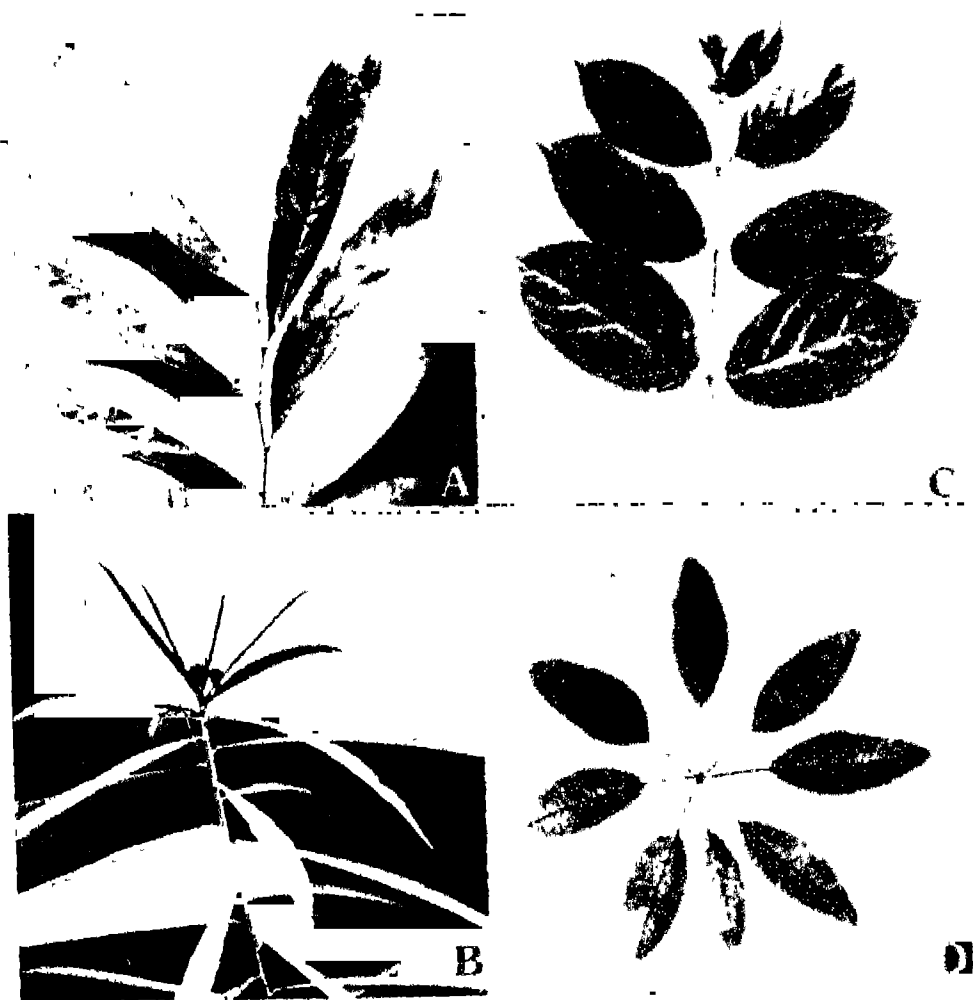


Fig. 26.27 Arrangement of leaves on the stem. A. Alternate in two rows; B. Spiral; C. Opposite; D. Whorled (Photo: H Y. Mohan Ram)

defence as in cacti (Fig. 26.28). The fleshy leaves of onion store sugars. The pitcher in the pitcher plants (*Nepenthes*, *Sarracenia*, etc.) is also a modified leaf. In plants such as the Australian acacia (*Acacia auriculiformis*) (see Fig. 26.29) the leaves are tiny and ephemeral. The petiole expands, becomes green and takes over the function of photosynthesis.

#### Importance of Studying Leaf Morphology

The purpose of giving a short account of the variety of vegetative plant organs, their shapes, arrangement and modifications is not to burden you with technical terms and examples. They are important for documenting accurate descriptions for identification and classification of plants. Plant physiologists have now recognised

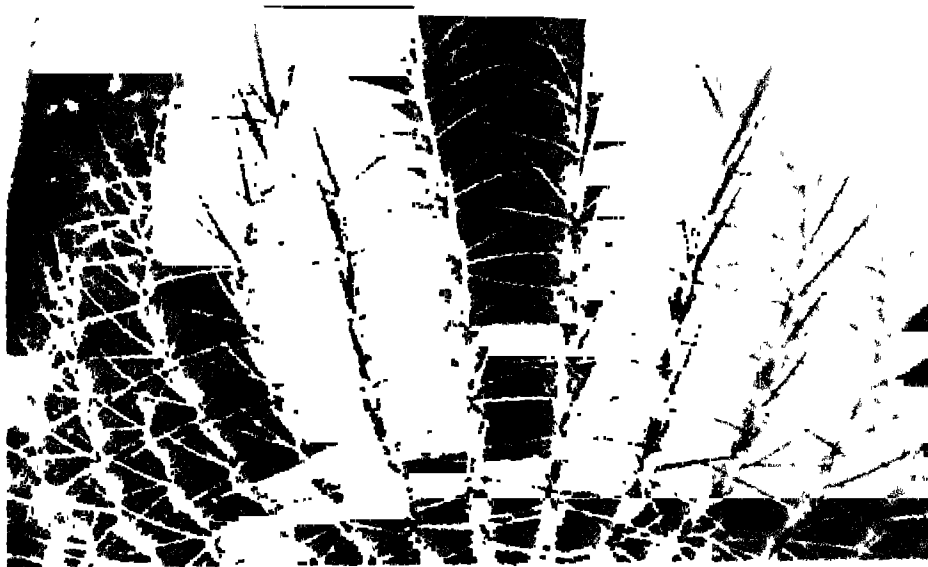


Fig. 26.28 Cactus showing modification of leaves into spines (Photo: H Y Mohan Ram)

that the stature of the plant, the rate of leaf production, internodal length, thickness, shape and area of leaves and their orientation to light, and periods up to which leaves are retained are important factors in determining crop productivity. In some perennial plants such as eucalyptus, leaves change shape during transition from the juvenile (non-flowering) to the mature (capable of flowering) stage. It is possible to tell the physiological maturity of a cotton plant by the shape of the foliage. Presence of leaves of more than one shape, observed quite commonly in amphibious plants, is termed **HETEROPHYLLY** (e.g. *Limnophila*, see Chapter 2). This feature may have adaptive significance. Horticulturists have selected, developed and propagated leaves of various shapes, sizes and colours, including variegated types. Foliage plants are an important item of horticultural industry.

### ANATOMY

In Chapter 4 you have learnt about the cell as a unit of life and the various roles cells



Fig. 26.29 Petiole modified into flattened lamina-like structures (*Ardisia nerioides*) (Photo: Dr M N H.Nair)

play in multicellular organisms. The first autotrophic cells were unicellular and arose in water. The unicellular organisms had access to the external medium. Even

the first multicellular forms were simple and communication between the constituent cells was not too difficult. However, when the plants invaded land, they were subjected to stresses of solar radiation, variation in temperature, wind and desiccation. The peripheral cells of the plant body were in direct contact with the outside, in contrast to those situated deep within. One important evolutionary development was intercellular communication through plasmodesmata.

You have learnt that plants are the largest living organisms. Most higher plants, with the exception of those with an aquatic habit, are immobile. Their roots are firmly anchored in the soil. They have an enormous surface which is essential to glean substances from the environment in extremely dilute concentrations. It is really a wonder how such large organisms can live for hundreds of years with a relatively simple internal structure. Moreover, plants cannot escape stresses like animal-invasion by moving away. They have to adjust themselves entirely by physiological means. This requires a high degree of coordination between structure and function.

Multicellular organisms consist of organ systems, resulting from cell division, cell enlargement and cell differentiation. Early in their formative stage cells look alike but are gradually organised into tissues; tissues to organs and organs turn into an organism.

One important feature of multicellular organisms is DIVISION OF LABOUR, which means sharing of functions. A group of cells having a similar structure and function is called a tissue. Plant tissues are composed of three basic systems: (i) dermal—such as epidermis, which is protective in its function; (ii) vascular—

xylem and phloem, which are conducting tissues; (iii) ground or fundamental—all tissues excluding dermal and vascular tissues (parenchyma, collenchyma, sclerenchyma). Each tissue contributes to the functioning of an organ. The leaf has an epidermis for protection and exchange of gases, mesophyll for carrying out photosynthesis and vascular tissue for conducting food, water and minerals. All these functions are coordinated to make the leaf an efficient organ for the synthesis of food. Each organism depends on the coordinated activities of its organs.

You will now learn about the nature and types of tissues and the patterns of their arrangement in vegetative organs.

### Types of Plant Tissues

Unlike animals, plants continually produce new tissues and organs till they die. This is accomplished by the presence of sites where active cell divisions occur. Tissues which are perpetually young and endowed with the capacity for cell division are called MERISTEMS. Based on their location and function, two kinds of meristems are recognised—apical and lateral. Apical meristems are found at the tips of shoots and roots. Cells formed in the apical meristems differentiate into primary tissues and cause increase in the length of the plant body. Buds in the axils of leaves also have apical meristems.

The lateral meristems (meristems arranged parallel to the sides of the organs) include CAMBium and CORK CAMBium (PHELLOGEN). They bring about an increase in the width or girth of the organ. A third kind of meristem, called INTERCALARY MERISTEM occurs at the bases of internodes and leaf sheaths of the monocotyledonous plants, particularly grasses.

In these plants vascular cambium is absent.

Permanent tissues consist of cells which do not normally divide but are differentiated to carry out various functions. A brief account of the structure and the main functions of PERMANENT TISSUES is given here.

### *Epidermis*

This tissue is generally one-cell thick and forms the surface-covering of the primary plant body. You will find leaves, flowers, young stems and roots covered by an epidermis. In the aerial parts of the plant, the outer walls of the epidermis have a waxy covering called the cuticle, which protects the plant from water loss, mechanical injury and invasion by pathogens. The epidermis of aerial parts of some plants bears one-to many-celled hairs or glands (Figs.26.30&26.31). Some hairs are secretory in function. The epidermis of the aerial parts of the plant is at the interface of the plant and the atmosphere. The epidermis of leaves and green stems have a large number of openings called STOMATA. You will study details about stomata later.

### *Parenchyma* <sup>Food</sup> STOMATA

The cells of parenchyma are generally thin-walled (xylem parenchyma is thick-walled), 12-14 sided and variously shaped. They retain the ability to divide at maturity (Fig. 26.32). Storage is the main function of parenchyma.

Specialised parenchyma cells as those seen in the periphery of a stem or in leaves, contain chloroplasts (CHLORENCHYMA) and carry out photosynthesis. AERENCHYMA is a specialised parenchyma tissue occurring in AQUATIC PLANTS, with a regular system of intercellular air spaces.

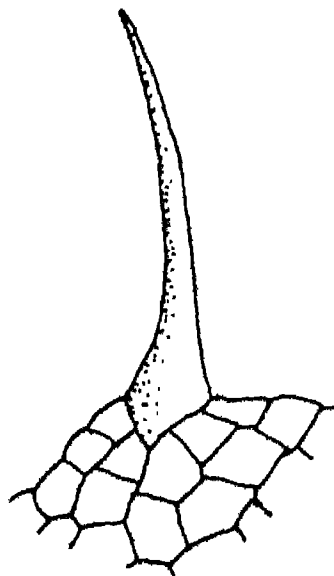


Fig. 26.30 A unicellular glandular hair

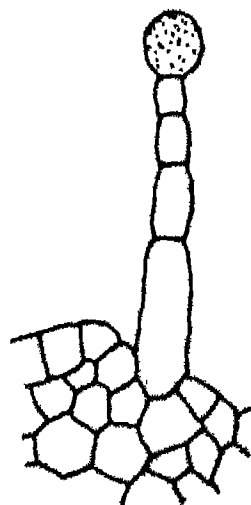


Fig. 26.31 A multicelled epidermal gland

### COTTON -- THE MIRACLE HAIR

Cotton, the most important textile fibre used the world over, consists of unicellular epidermal hairs of seeds of a few species of *Gossypium*. The number of lint hairs borne by a single seed may exceed 10,000. It is one of the few eucaryotic cells that can be seen by the naked eye. It is estimated that one kilogram of cotton contains over 200 million hairs.

#### Collenchyma *stronger*

The cells of collenchyma appear polygonal in cross section. They have unevenly thickened walls which are prominent at the corners (Fig. 26.33). The principal role of collenchyma is to give strength and flexibility to growing organs like young stems.

#### Sclerenchyma *stronger (old)*

This tissue is composed of dead cells with thick, lignified walls. Sclerenchyma lends mechanical support to the organs and helps them to withstand various physical stresses. Sclerenchyma has two types of cells the FIBRES and the SCLEREIDS which differ in size and shape. FIBRES are elongated and flexible, with tapered ends (Fig. 26.34). Some sclereids are called stone cells. They are irregular in shape with highly thickened walls and a narrow lumen (Fig. 26.35). Sclereids are commonly found in the shells of nuts, and in the pulp of guava, pear and sapota fruits (the grittiness of the pulp in these fruits is due to the presence of stone cells).

#### Vascular Tissue *xylem → wood*

This is a conducting-tissue, composed of xylem and phloem. Xylem is mainly concerned with the transport of water and minerals. Food and other organic substances are translocated in the phloem. Xylem is also called WOOD and forms the bulk of the roots and stems of vascular

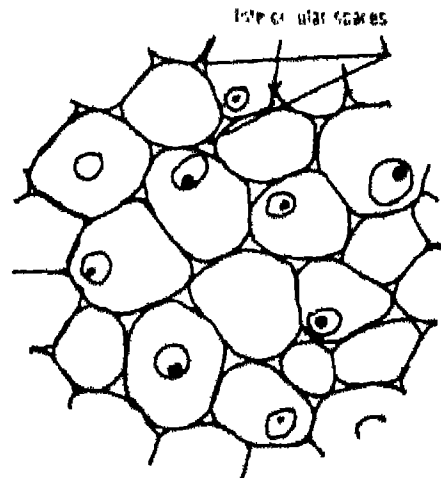


Fig. 26.32 Parenchyma cells with intercellular space.

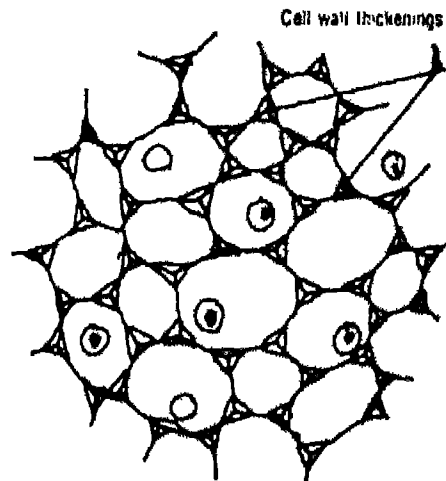


Fig. 26.33 Collenchyma cells with prominent thickenings at the corners



Fig. 26.34 An isolated fibre

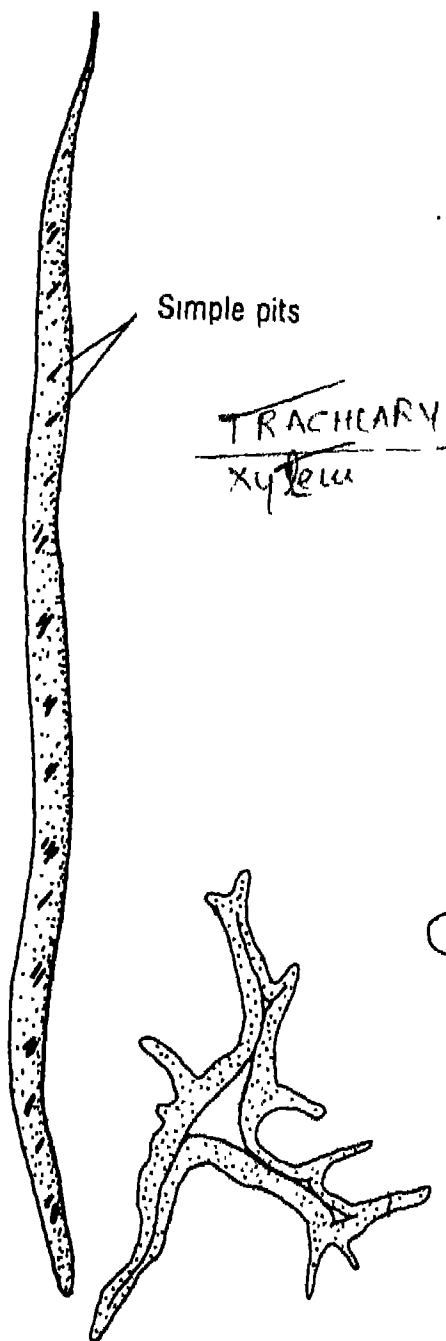


Fig. 26.35 A sclereid

plants. It also provides support and storage.

As a conducting tissue, xylem forms a continuous channel through the roots, stems, leaves, flowers and fruits. The conducting cells of xylem are called TRACHEARY ELEMENTS. Two types of tracheary elements are recognised—TRACHEIDS and VESSEL MEMBERS (Fig. 26.36). Tracheids are predominant in lower vascular plants, whereas vessels (formed by the dissolution of end walls of developing vessel members) occur in angiosperms.

The vessel members have perforations in their end-walls. The end walls of tracheids lack them (Fig. 26.36A). If an end wall has several openings, it is termed a MULTIPLE PERFORATION PLATE (Fig. 26.36B). If it has one opening, it is known as SIMPLE PERFORATION PLATE (Fig. 26.36C). Both tracheids and vessels have thick lignified walls with unthickened areas called pits. Two adjoining vessels or tracheids exchange water through their pits. At maturity both vessels and tracheids are dead.

In addition to conducting elements, xylem contains fibres and parenchyma cells. Fibres are generally dead and their primary function is to provide support. The parenchyma cells are living and are mainly involved in the short-distance transport of substances and storage of sugars, starch and lipids.

Phloem consists of conducting cells called SIEVE ELEMENTS which are of two types: (i) SIEVE CELLS (Fig. 26.37A,B) are most commonly present in the lower vascular plants; (ii) SIEVE TUBE MEMBERS (Fig. 26.37C,D) are found in angiosperms. In sieve cells, the openings at certain areas of the cell wall (sieve areas) occur throughout the end walls and lateral walls. However, in SIEVE TUBE MEMBERS large open-

ings (sieve pores) occur mainly on the end walls (SIEVE PLATE). A mature sieve element is living but it lacks a nucleus.

Sieve tube members are usually associated with specialised parenchyma cells called COMPANION CELLS. These cells help the sieve tube members in the translocation of food material. Besides sieve elements and companion cells, the phloem tissue contains parenchyma and phloem fibres. Phloem parenchyma cells mainly store food material while phloem fibres provide mechanical support. Phloem fibres of plants such as jute, flax and hemp are retted in water and extracted. They are used for making threads, ropes and coarse textiles.

Stem *tuip* → outside

The stem which is the axis of the shoot system, is generally cylindrical or quadrangular.

The apical bud of the stem encloses the shoot apex. It contributes to the extension growth of the stem and the formation of leaves. At the time of flowering, the shoot apex produces floral structures. The histology of the shoot apex varies considerably in angiosperms, gymnosperms and lower plants.

In flowering plants it consists of one or more outer layers called the TUNICA and a central mass of cells called the CORPUS (Fig. 26.38). The central region below the corpus becomes the PITH and the flanks produce PROCAMBium, CORTICAL CELLS and LEAF PRIMORDIA (Fig. 26.38). Thus the shoot apex gives rise to the primary tissues of the shoot.

The PROCAMBium initiates close to the apical meristem. It consists of narrow, elongated, densely cytoplasmic cells arranged parallel to the longitudinal axis of the stem. It is from the procambium

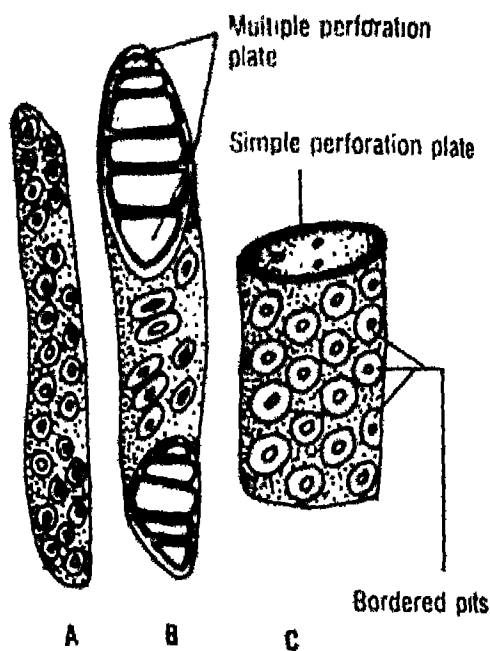
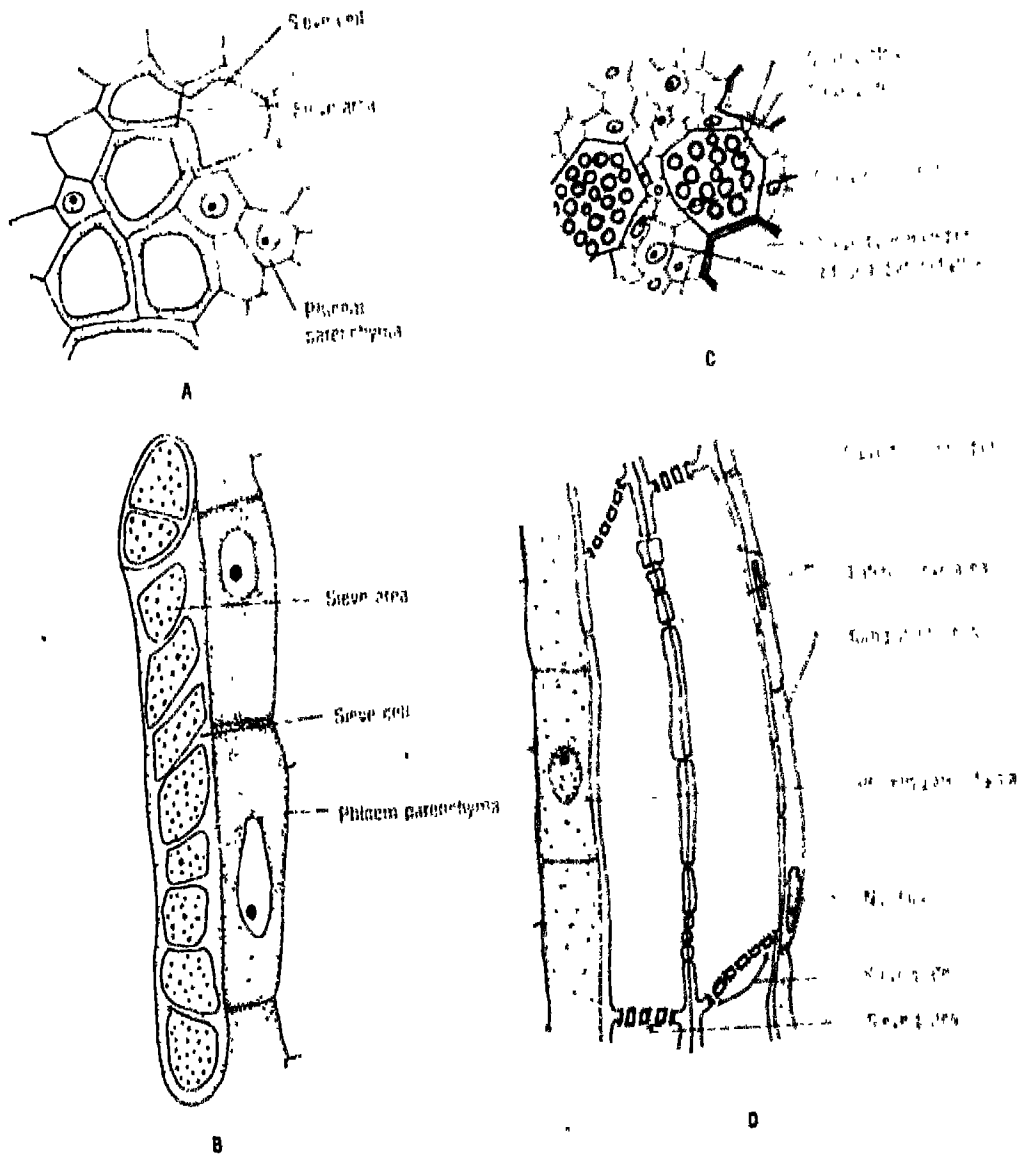


Fig. 26.36 Tracheid (left) and vessel members  
A. Tracheid, B. Vessel member with multiple perforation plate, C. Vessel member with simple perforation plate

that the primary phloem and xylem are differentiated. In plants showing secondary growth, some procambial cells remain meristematic and give rise to the vascular cambium.

The fundamental tissues that can be recognised in the stem after primary growth are : epidermis, cortex, endodermis, vascular tissue and pith (Fig. 26.39B). The extent and arrangement of these tissues is varied, based on the nature of the plants and also in the different parts of the same plant.

The epidermis is usually single-layered. It generally has stomata and trichomes. Internal to the epidermis is the CORTEX. It consists of parenchyma cells and a large proportion of collenchyma cells. The cortex functions as a protective tissue in the

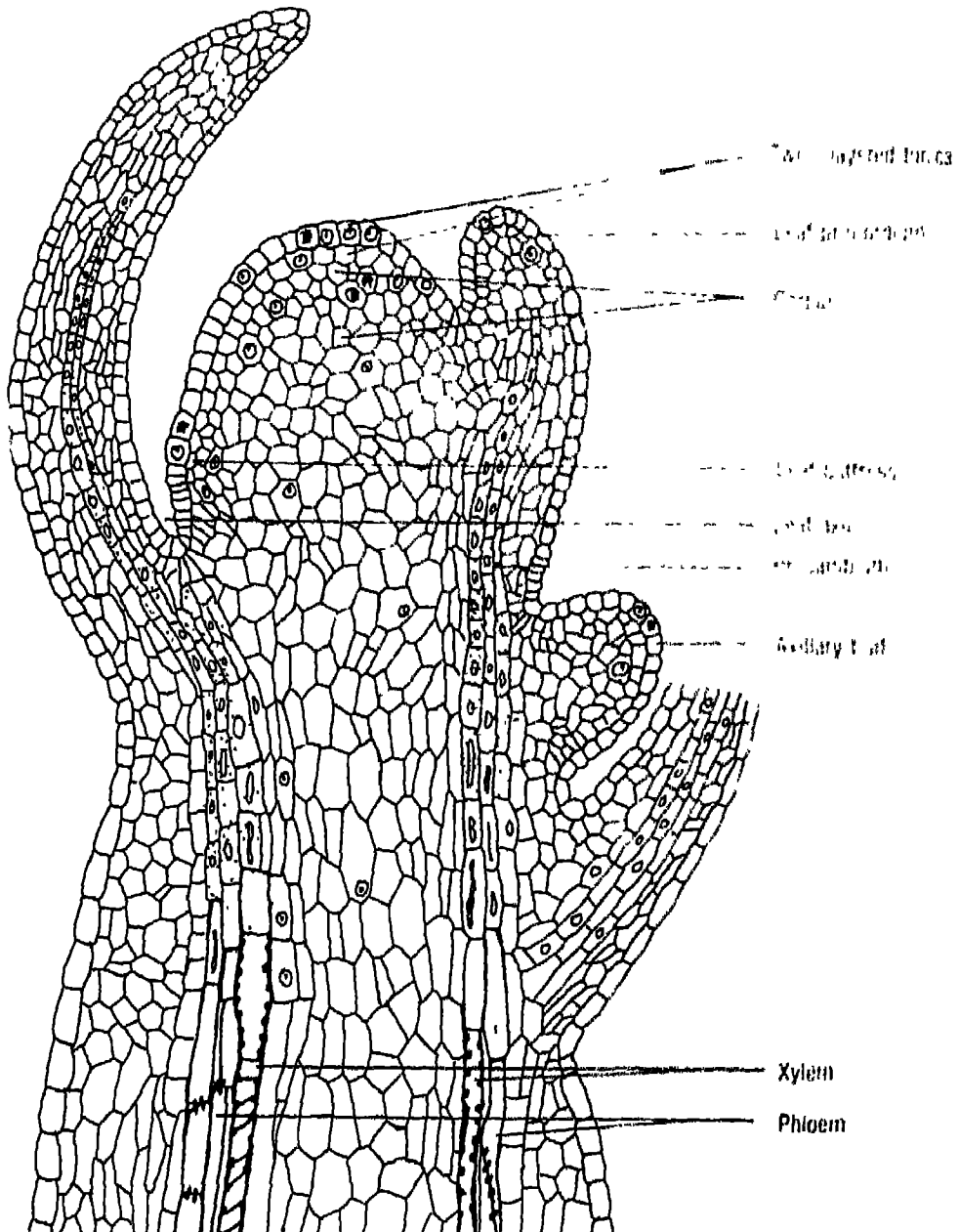


**Fig. 26.37** Components of phloem  
 A. Sieve cell in cross-section, B. Sieve cell in longitudinal section, C. Cross-section of phloem of an angiosperm; D. A longitudinal section of phloem of an angiosperm showing sieve tube members, companion cells and phloem parenchyma

primary plant body, besides providing support and storing reserve materials. In a young stem the cortical cells contain chloroplasts and carry out photosynthesis.

A uniseriate layer termed **ENDODERMIS** separates the vascular tissue from the cortex.

The primary vascular tissue develops



**Fig. 26.38** A longitudinal section of shoot apex showing apical meristem, young leaf primordia and an axillary bud

from the PROCAMBIUM. The vascular tissue is dispersed as bundles or strands consisting of phloem and xylem. Each strand is called a **VASCULAR BUNDLE**. In the dicotyledons the vascular bundles have a meristematic tissue called **CAMBIUM** between xylem and phloem (Fig. 26.39A). In the monocotyledons cambium is absent and the vascular bundles are scattered randomly or may be arranged in two or more rings (Fig. 26.40). In the dicotyledons vascular bundles are arranged in a ring. A vascular bundle which contains cambium is called an **OPEN BUNDLE** (Fig. 26.39B). A bundle lacking cambium is called a **CLOSED BUNDLE** (Fig. 26.40B).

The vascular bundle is termed **COLLATERAL** when it has a xylem and a phloem pole (It is **BICOLLATERAL** when there are two phloem poles at each end of the xylem, with only one central cambium layer). In a stem the first formed xylem (protoxylem) is located toward the pith and later formed xylem (metaxylem) toward the outside. This arrangement of xylem is termed **ENDARCHY** (Fig. 26.39B).

The centre of the stem consists of parenchyma cells and is called the **PITH**. The structure of the nodes differs from that of the internodes because the former bear leaves. The vascular tissues at the nodes are branched and show divergent arrangement to form a continuous strand from the stem to the leaves. *Branch*

**Secondary Thickening:** You have learnt that increase in plant height is achieved by cell divisions and cell elongation in the terminal part of the shoot. There is a corresponding enhancement in the thickness of the stem to meet the demands of the increasing height and weight of the stem and its branches. This is accomplished by increase in the amount of vascular tissue

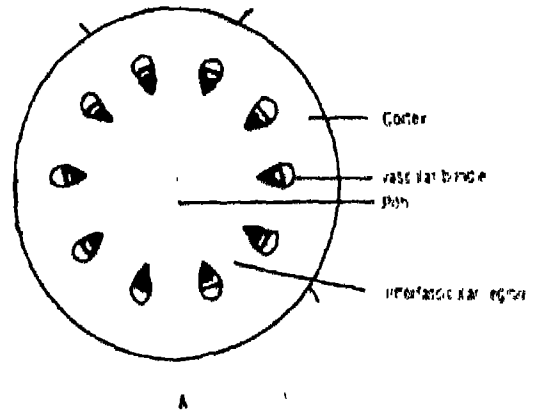


Fig. 26.39A Cross section of a young stem of a dicotyledon. Note the arrangement of open vascular bundles in a ring.

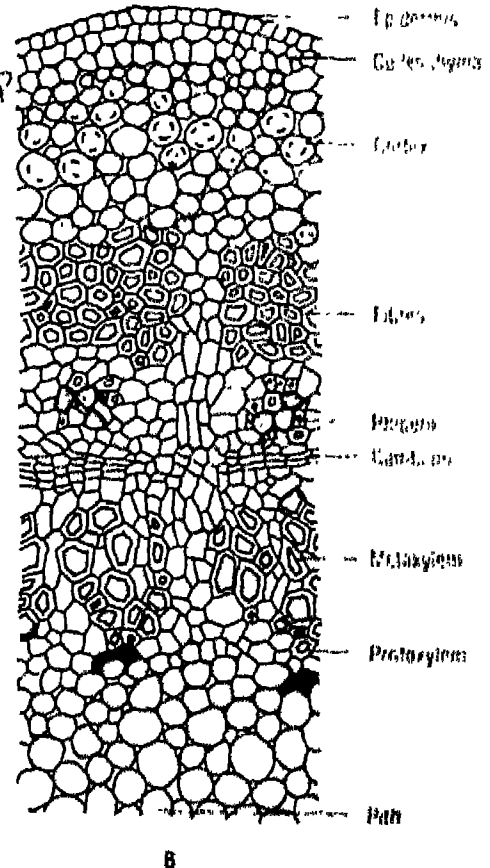


Fig. 26.39B An enlarged view of a portion of Fig. 26.39A to show histological details.

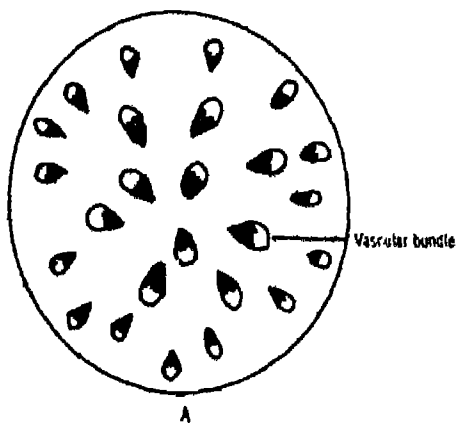


Fig. 26.40A Cross-section of a monocotyledonous stem. Note the scattered vascular bundles.

by secondary growth. Secondary vascular tissues are produced by the vascular cambium. This is characteristic of dicotyledons and gymnosperms. In some exceptional monocotyledons, increase in the thickness of stem occurs by a special form of secondary growth.

You would recall that the vascular bundles in dicotyledons have cambium between xylem and phloem. This cambium is known as FASCICULAR CAMBIUM (Fig. 26.41A). It is interconnected by the formation of meristem from the parenchyma cells between the vascular bundles. This meristem is called INTERFASCICULAR CAMBIUM. Thus the fascicular and interfascicular cambium join together to form a complete cylinder around the axis (Fig. 26.41B). The cells produced by the divisions of fascicular and interfascicular cambia differentiate into phloem toward the outside of the axis and xylem toward the inside (Fig. 26.41C,D; Fig. 26.42). In species where secondary growth occurs in the stem and the root, the secondary protective tissue—the

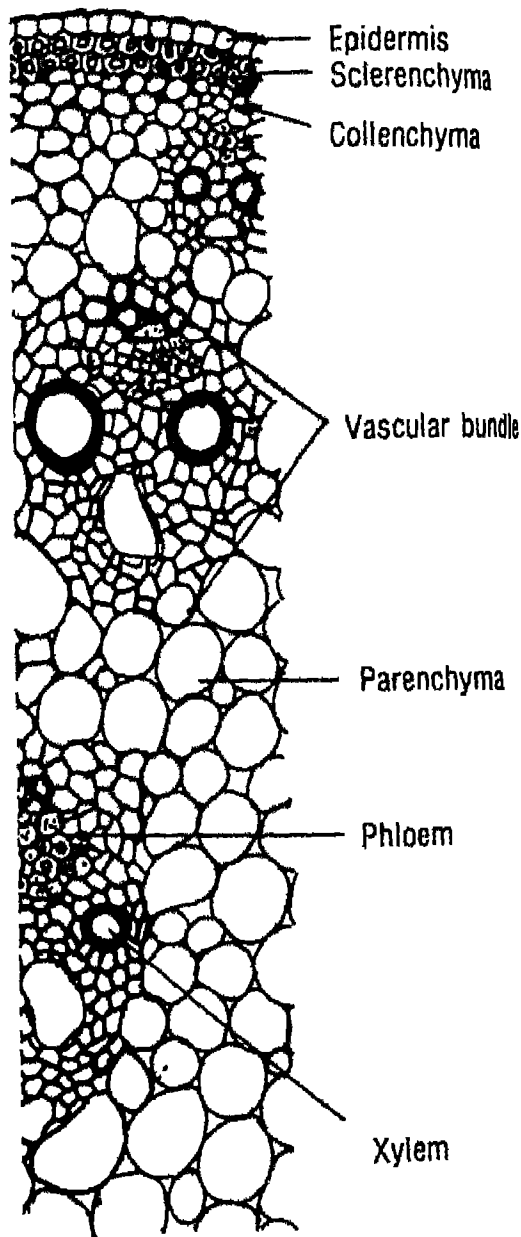


Fig. 26.40B An enlarged view of a portion of Fig. 26.40A to show histological details

x P Stem

periderm—replaces the epidermis. The periderm consists of PHELLOGEN (cork cambium) which produces PHELLEM (cork) toward the outside and PHELLODERM (secondary cortex) toward the inside.

In certain plants the secondary growth does not occur as described above. The deviating kinds of secondary growth are known as ANOMALOUS SECONDARY GROWTH (*Aristolochia*, *Bougainvillea*).

### Leaf

A leaf is often referred as a food factory of

the plant as it is in this organ that the bulk of photosynthesis occurs. It is also an organ from which water evaporates in profuse quantities. The leaf has a large surface and an extensive system of air spaces. Leaves show a wide range of shapes and sizes as you have already studied.

The epidermis covers the upper surface (adaxial epidermis) and lower surface (abaxial epidermis) of the leaf (Fig. 26.43A). The epidermis is interrupted by a large number of openings called stomata (stoma, singular). Thus the

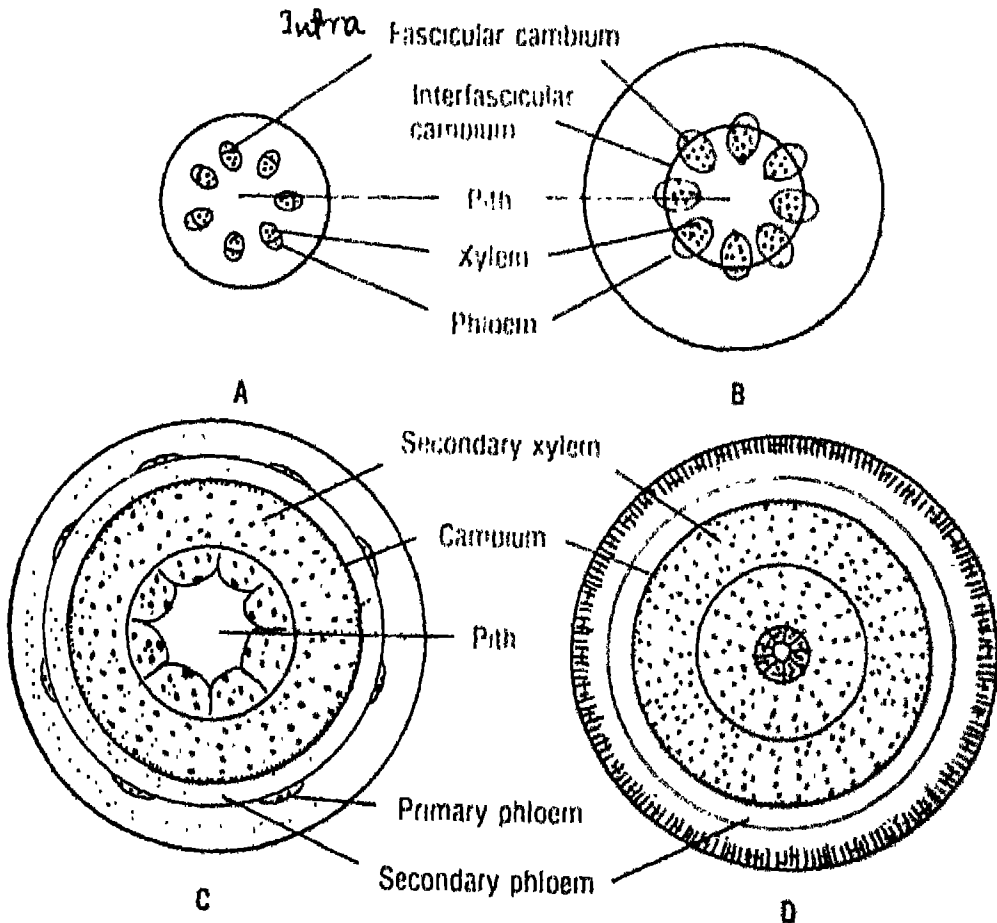
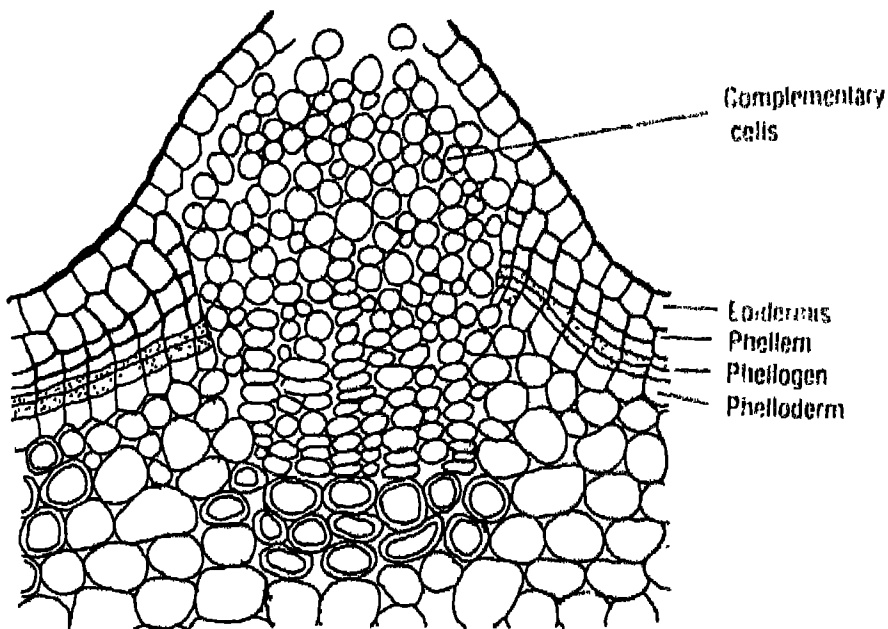


Fig. 26.41 Stages in secondary growth of stem (diagrammatic)

## CORK

Mature woody stems have a peripheral water proof tissue called cork. It is composed of dead cells with thick walls impregnated with a waxy material called suberin. Cork is formed by cork cambium (phellogen), a lateral meristem, which replaces the epidermis in stems and roots of older woody plants. Although some amount of cork is present in many plants, it is only from the cork oak tree (*Quercus suber*) that commercial cork can be harvested as sheets every few years. The tree is a native of the western mediterranean region. Cork insulates trees from freezing temperatures in the cold winter and also helps in the conservation of water. Cork shows openings in the form of scars on its surface. These are called LENTICELS. These openings permit the exchange of gases between the atmosphere and living cells below the cork. Cork is light, highly compressible and does not catch fire easily. One of the oldest uses of cork is as a stopper for bottles. Because it is non-reactive and undamaged by liquids, cork has been an ideal material for centuries for corking wine bottles and casks. More recent uses of cork include manufacture of insulation boards, shock absorbers, linoleum, sports goods, etc.



Young lenticel



epidermis of the aerial part of the plant is the layer which is at the interface of the plant and the atmosphere. Each stoma is surrounded by two kidney-shaped cells called the **GUARD CELLS** (Fig.26. 43B). The opening and closing of the stomata are determined by the expansion and contraction of the guard cells. Stomata regulate the exchange of gases and the loss of water vapour from the leaves.

The tissue enclosed between the two epidermal layers is called the **mesophyll** (this name is derived from the Greek words *Meso* = middle and *Phyllan* leaf). The mesophyll consists of elongated cells arranged in rows or stacks called the **PALISADE PARENCHYMA** and/or irregularly arranged cells with large intercellular spaces, known as the **SPONGY PARENCHYMA** (Fig.26.43A). The mesophyll cells contain abundant chloroplasts. The proportion of the palisade to spongy parenchyma depends on the habitat of the plant. More palisade tissue occurs in leaves exposed to bright light during development than those exposed to shade.

The vascular bundles in the leaf are located in the midrib and the veins. In each vascular bundle of the leaf the phloem is located toward the abaxial side and xylem toward the adaxial side.

Root

Root is the underground part of the plant axis. Most gymnosperms and the dicotyledons have a TAP ROOT SYSTEM.

The histology of the root apex differs in different plants. The root apical meristem is subterminal because it is covered by a protective ROOT CAP (calyptra) (Fig.26.44) produced by a meristematic zone called the CALYPTROGEN. The root cap acts as a buffer between the soil and



Fig. 26.42 A magnified view of a portion of cross-section of stem after secondary growth

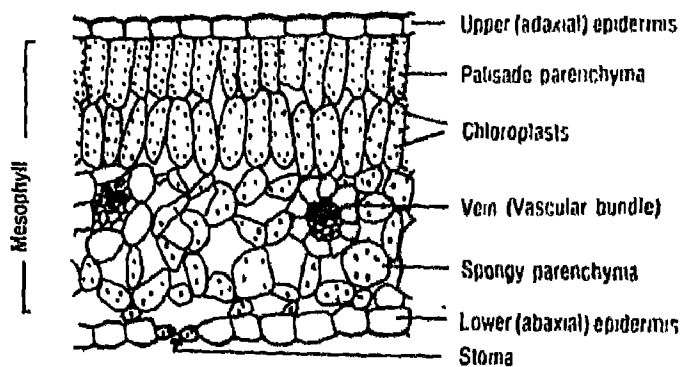


Fig. 26.43A Cross-section of a portion of a leaf showing mesophyll tissue and vein

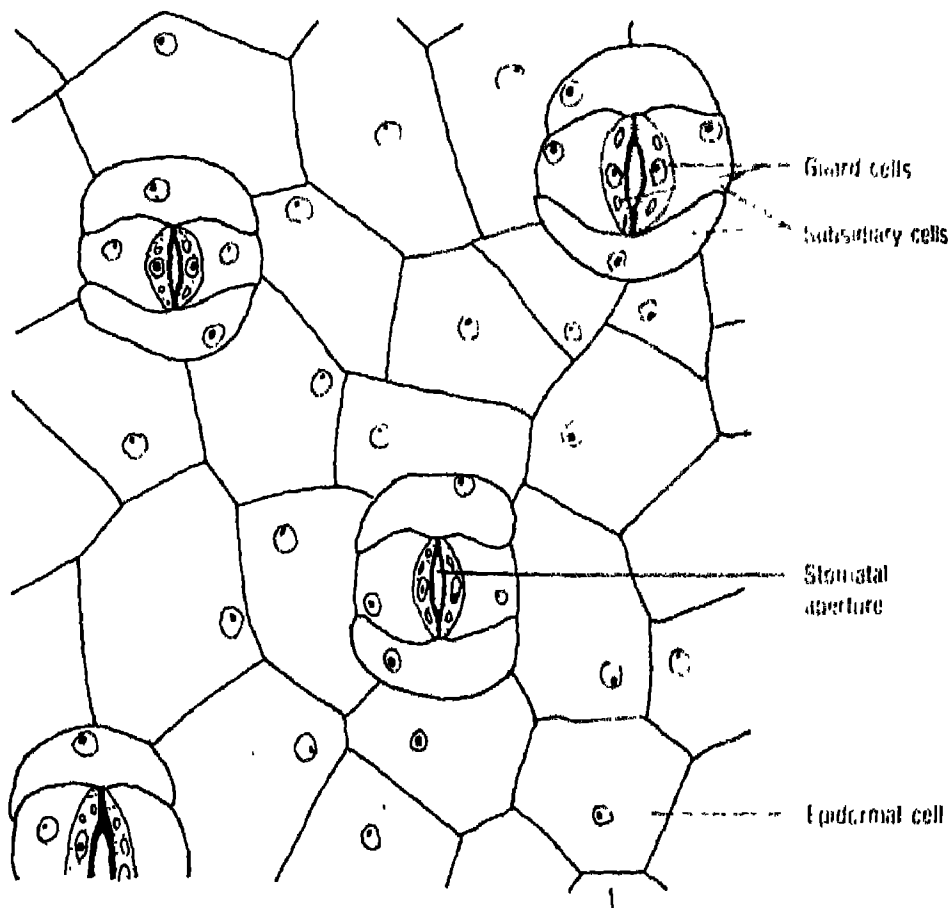


Fig. 26.43B Portion of epidermis enlarged to show stomata

Root 2014  
 1. Root cap  
 2. Root hairs  
 3. Root cortex  
 4. Root endodermis  
 5. Root xylem  
 6. Root phloem  
 7. Root pericycle  
 8. Root epidermis

the apical meristem. The root apex does not produce any lateral organs. The root apex, which gives rise to different types of tissue may or may not exhibit meristematic zonation. The root apex has a zone of slowly dividing cells in the middle of highly meristematic cells. This is known as the QUIESCENT CENTRE.

The root has a uniseriate epidermis. It forms outgrowths called ROOT HAIRS from the region just behind the zone of elongation. Root hairs are invariably unicellular and are formed in great profusion. They are principal sites of absorption of water and minerals. They are short-lived and are replaced continuously.

The root cap has the appearance of a thimble and protects the root meristem. The cells of the root cap secrete a mucilaginous substance that acts as a lubricant. Without this adaptation, it would have been almost impossible for the tender root tips to enter the hard crust of the soil. The root cap cells are also short-lived. They are parenchymatous and contain starch grains. It is believed that the starch grains are responsible for the geotropic response of the roots.

The root cortex consists of parenchyma cells (Fig. 26.45). In monocotyledons the cortical cells may become sclerenchymatous. Usually the cortical cells have no chloroplasts but the roots of water plants and epiphytes (plants living on other plants) may have them.

The inner-most layer of the cortex develops into a specialised layer called the endodermis. In all most all the roots the endodermis has a peculiar band-like thickening made of lignin and suberin on the anticlinal walls (radial and transverse) (Fig. 26.45). This band is known as the CASPARIAN STRIP. It prevents plasmolysis in the cells of the endodermis and allows

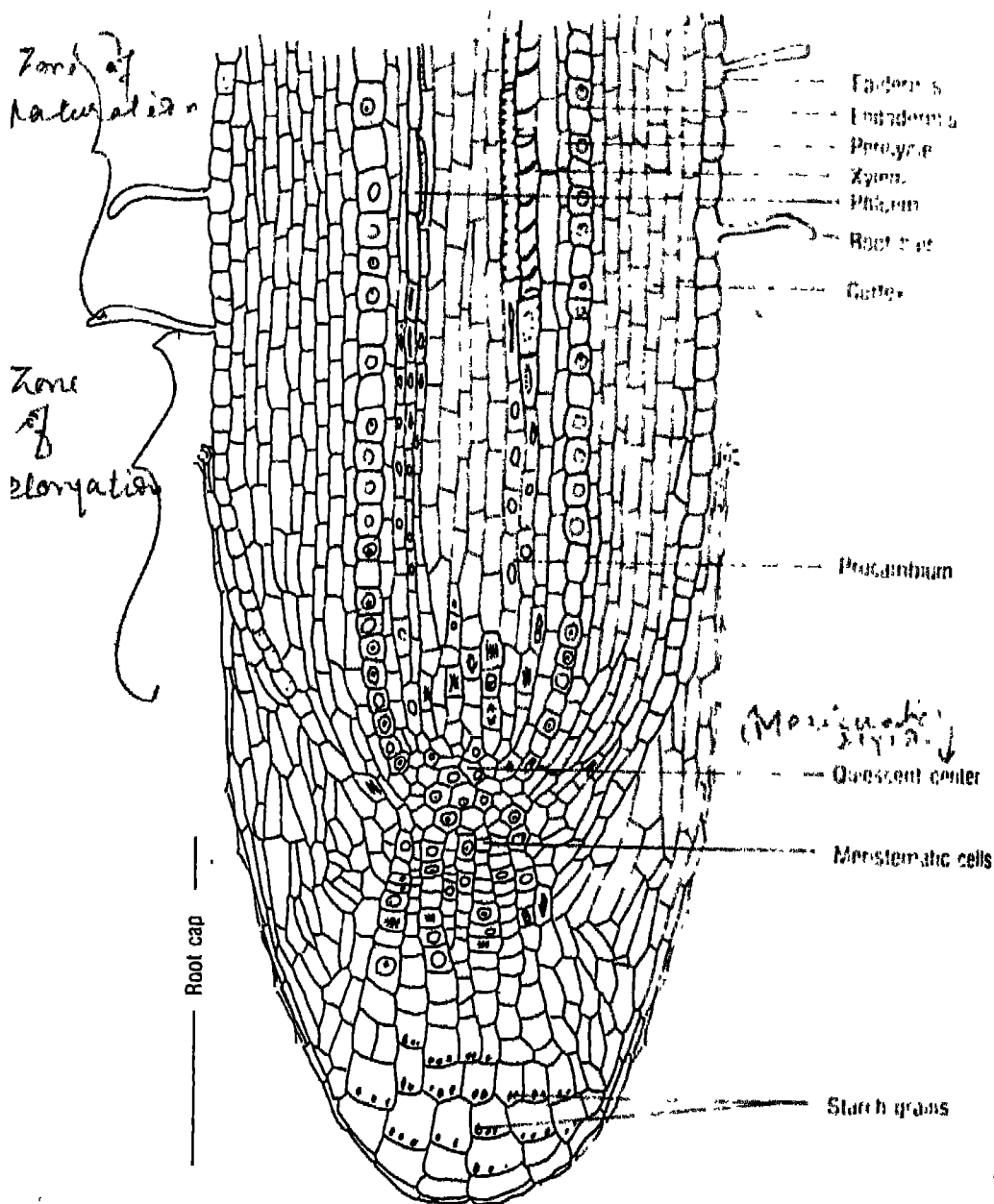
the soil water to pass across.

The vascular tissue of the root is surrounded by a uniseriate or multiseriate tissue called PERICYCLE. In a young root the pericycle is parenchymatous. In monocotyledons which do not show secondary growth, the pericycle undergoes lignification in the older roots. The roots of certain water plants and parasites do not have pericycle. The lateral roots generally originate from the pericycle (endogenous origin).

The vascular tissues of the root are seen as discrete strands of phloem, alternating with xylem. Dicotyledons have two (diarch), three (triarch), four (tetraarch) (Fig. 26.46), five (pentarch) or six (hexarch) strands. A root containing more than six strands is known as POLYARCH. Most of the monocotyledonous roots are polyarch (Fig. 26.47). In the dicotyledonous roots the xylem generally occupies the centre. If no xylem is present in the centre, as in the case of monocotyledonous roots, it is occupied by a parenchymatous pith. In the root, the PROTOXYLEM is located toward the periphery of the vascular cylinder and METAXYLEM toward the centre (exarch xylem) (Fig. 26.45).

Inside ← [MX PX] →

Secondary Thickening: Secondary growth occurs in the roots of most dicotyledonous plants with the exception of a few short-lived herbs and submerged aquatics. In the root the secondary vascular tissue is first formed in the region between the primary xylem and the phloem. A cambial ring is formed by the joining of the vascular cambium on the inner edge of the phloem (Fig. 26.48A) with the cambium differentiated from the cells of the pericycle outside the protoxylem (Fig. 26.48B). The derivatives of the cambium differen-



**Fig. 26.44** A longitudinal section of root apex showing apical meristem, root cap and different types of tissues

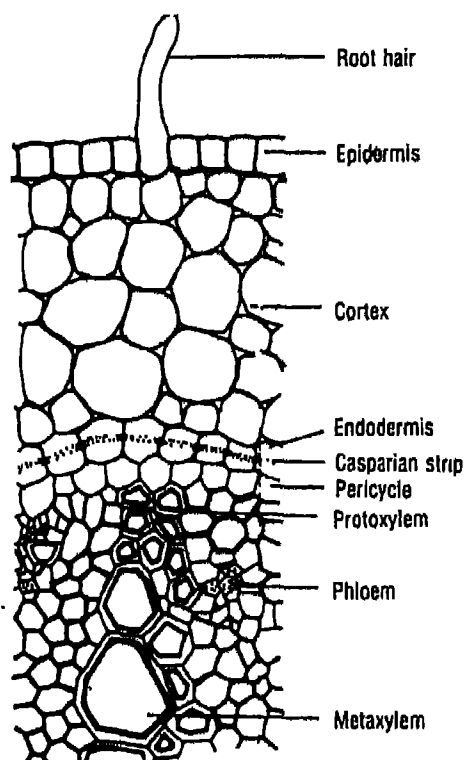


Fig. 26.45 Cross-section of a portion of dicotyledonous root showing histological details

tiate into secondary xylem toward the inside of the root axis and secondary phloem toward the outside (Fig. 26.48C,D).

### Wood

Wood is the principal product of metabolism of trees and it forms the bulk of their body. Wood is unique among the important renewable raw materials. People have been using wood even before metals were discovered. It is a source of fuel, timber, shelter, tools and furniture. Around 4000 B.C. Egyptians built ships out of cedar wood imported from Lebanon. An

unknown Greek woodman invented a primitive wooden lathe which heralded the era of the first machines.

Let us study how wood is formed and what are its important features. Botanically, wood is secondary xylem formed by vascular cambium during secondary growth. Vascular cambium consists of two types of initials: (i) FUSIFORM INITIALS that produce elongated xylem elements such as tracheary elements (vessels and tracheids), fibres and axial parenchyma cells, and (ii) RAY INITIALS that produce cells horizontal to the longitudi-

Fig. 26.46 Cross-section of a dicotyledonous root showing the arrangement of xylem and phloem (vascular tissue)

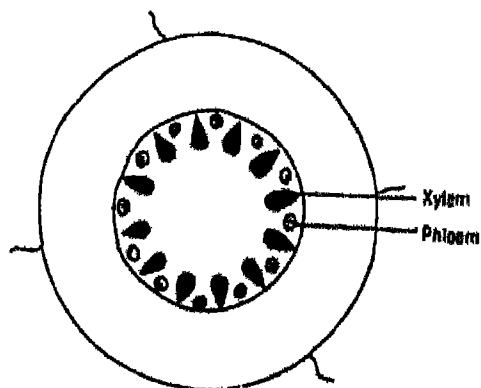
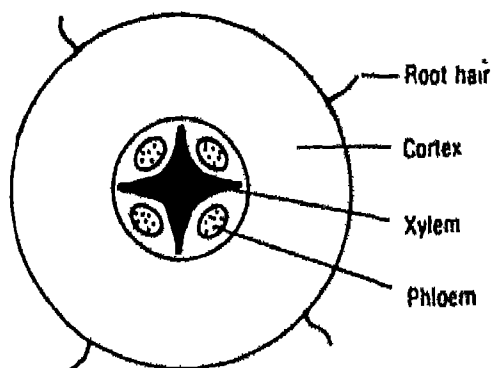


Fig. 26.47 Cross-section of a monocotyledonous root showing polyarch vascular tissue

nal axis of the stem (rays). The tissue components of the wood show specific features which are important in wood identification.

**Softwood and Hardwood:** The wood produced by gymnosperms is commercially called **SOFTWOOD**. This term does not mean that the wood is soft. In fact, coniferous woods are quite hard. Soft wood is also known as non-porous wood because it lacks vessels.

The wood of dicotyledonous trees is called **HARDWOOD** or **POROUS WOOD**. It has **vessels (pores)**. If you examine a transverse section of a log by a hand lens you can easily tell whether it is softwood or hardwood. The softwoods are made of **90-95 per cent of tracheids** and **5-10 per cent of ray cells**. The tracheids transport water and give support to the tree and the rays serve as channels for radial transport and to store products of photosynthesis. Hardwoods are composed of vessels (some-

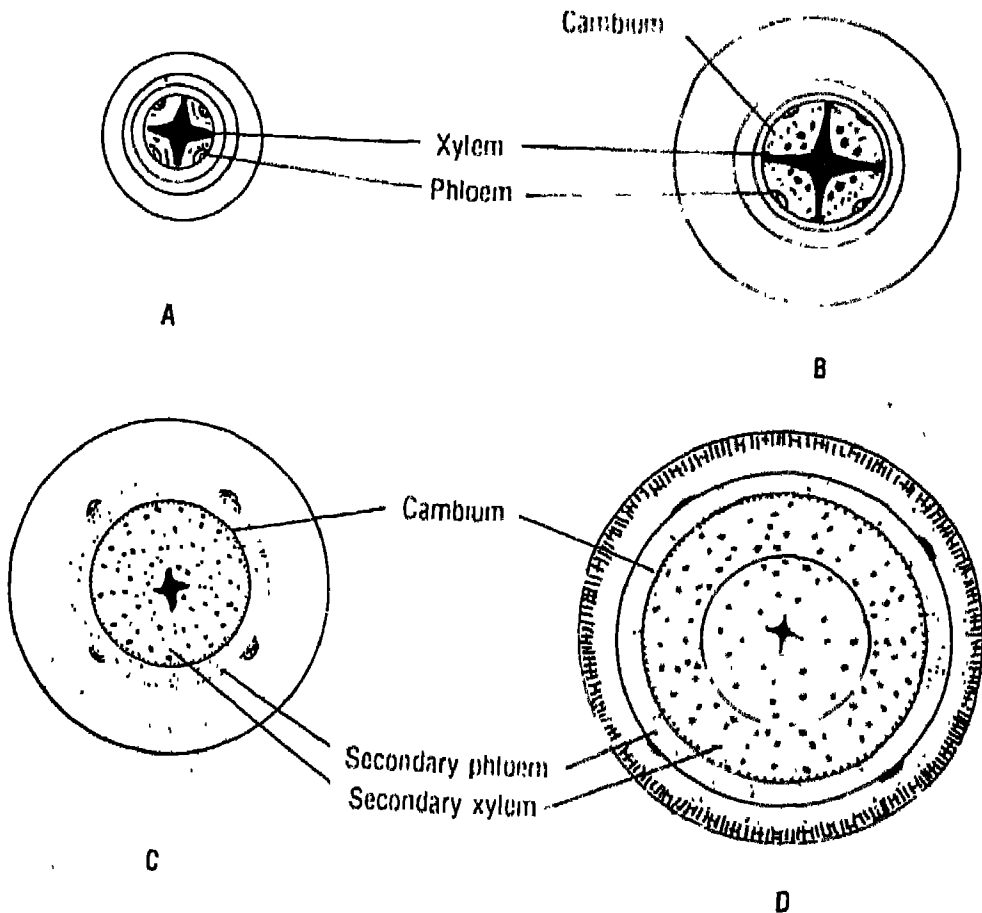


Fig. 26.48 Stages of secondary growth in root (diagrammatic)

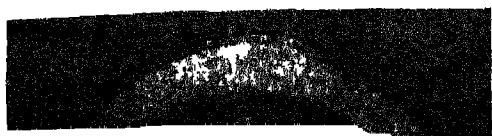


Fig. 26.49 Cross-section of a log of teak to show sapwood and heartwood  
(Photo: Dr. M.N.B.Nair)

times tracheids), fibres and parenchyma.

**Sapwood and Heartwood:** After certain years of growth several woods develop dark colouration in the centre. This dark coloured wood is dead and is called **HEARTWOOD**. The peripheral, light-coloured living wood is called **SAPWOOD** (Fig.26.49). Heartwood contains organic compounds like oil, aromatic substances, gum, resins, tannins, and other coloured materials. These substances are collectively known as **EXTRACTIVES**. Heartwood is more durable and resistant to microorganisms and insects than sapwood.

The activity of cambium is influenced by environmental conditions. During favourable seasons (spring and summer) <sup>1141</sup> cambium is active and produces large vessels or tracheids (EARLYWOOD). In adverse climatic conditions (autumn and winter) the vessels and tracheids produced are small (LATEWOOD). The xylem formed during one growth period is called an ANNUAL RING. In temperate regions

annual ring has prominent vessels in earlywood and narrow ones in latewood. Wood has large and small vessels in distinct parts in an annual ring. Such woods are called **RING POROUS** woods (Fig.26.50). In the tropics there is no sharp distinction of seasons and the wood contains vessels of the same size in latewood and earlywood. Such woods are called **DIF-FUSE POROUS** (Fig.26.51).

**Wood as a Raw Material:** Wood has been used for various purposes from pre-historic times. Even in modern times wood is a versatile material and is universally used as an engineering and industrial raw material. The greatest asset of wood is that it is renewable.

The features that make wood unique are the following:

1. It is light and can be transported over distances at a reasonable cost.
2. Fluctuations in temperature cause little change in the volume of wood.
3. It is a poor conductor of heat, electricity and sound. Wooden houses are warm in winter and cool in summer.
4. Wood is easy to work with. It can be cut, shaped, peeled and joined by glues, nails, screws or bolts. Many simple tools and implements can be made for household uses by people.
5. Wood holds paint, lacquer, varnish and other finishing materials because of its porous nature.
6. Wood is strong and absorbs shock loads and vibrations better than metals.
7. It does not rust or crystallise.
8. Being fibrous, wood is easily converted into pulp, which is used for the manufacture of paper, plastics, rayon and transparent film.
9. Above all, wood is beautiful and



Fig. 26.50 Cross-section showing ring porous wood (Photo: Dr. M. N. B.Nair)

The following are a few limitations of wood:

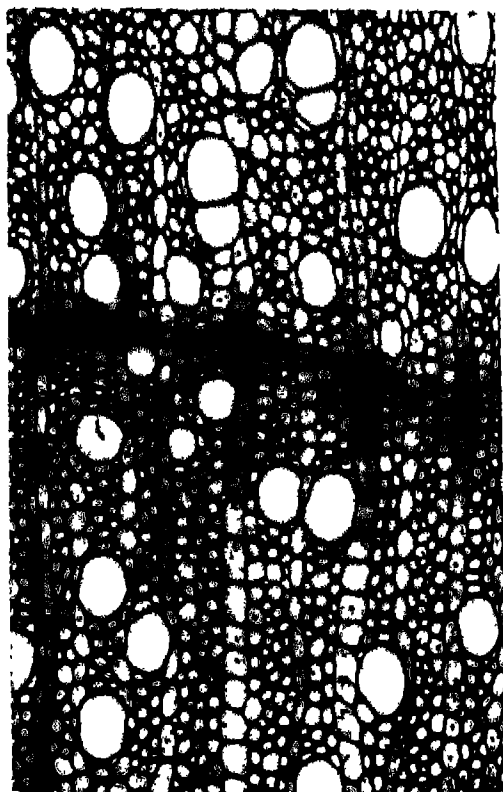
1. Its mechanical and physical properties cannot be changed or improved by heating.
2. It cannot be rolled into new shapes.
3. It is an organic material subjected to infection by microorganisms and decay.
4. Wood is combustible. It ignites spontaneously at  $275^{\circ}\text{C}$ .

Petroleum and other fossil energy sources are being rapidly depleted. Therefore, production of wood-derived fuel and chemicals through thermal, chemical and biological methods has become very important. You will learn about the various uses of wood and wood products later.

### Importance of Studying Anatomy

Besides enriching our knowledge of plant structure, anatomical studies help us in solving taxonomic problems. Food adulteration is a commercial malpractice. The microstructure of adulterated spices, coffee, tea, vegetable dyes, tobacco, saffron, asafoetida (*heeng*), plant drugs and other vegetable materials can be microscopically determined. PHARMACOGNOSY (the science which deals with the sources, characteristics and possible uses of medicinal substances in their natural or unprepared state) heavily depends on anatomical studies. Timber is becoming scarce and very often cheap and inferior woods are

Fig. 26.51 Cross-section showing diffuse porous wood (Photo: Dr. M. N. B Nair)





used in place of certified woods for construction, furniture, ship-building, vehicles, etc. Wood anatomy can help in differentiating the spurious material from

the standard woods. Forensic experts require the knowledge of plant anatomy to identify small pieces of plants or their products for solving criminal cases.

## SUMMARY

The plant body has two main systems—the root and the shoot. The root system anchors the plant in the soil and aids in absorption of water and minerals. Roots may be modified to serve the function of storage of food and vegetative propagation. The shoot is branched and bears leaves, flowers and fruits. Based on the height and strength of the stem, plants are classified into herbs, shrubs and trees.

Stems are generally negatively geotropic and aerial. However, variously modified underground stems occur. These are rhizome, bulb, corm and tuber. These serve as organs of food storage and propagation. Runner, sucker and stolon are examples of semi-arid regions are often leafless and their stems are green and photosynthetic.

Leaves are the main photosynthetic organs of the plant and originate from the shoot apical meristem in a definite sequence. The outline of the leaf-blade, margin and tip show an enormous variation. The veins of the leaf-blade are reticulate in a dicotyledon and parallel in a monocotyledon. A leaf is called compound when the lamina is incised completely to form independent leaflets. A compound leaf may be pinnate or palmate. In insectivorous plants leaves are modified to trap insects.

The plant height, rate of leaf production, internodal length, leaf arrangement, laminal thickness, shape, orientation to light and period of retention on the plant are features that contribute to crop productivity.

Internally the plant organs are composed of various types of tissues, each with a specific structure and function. The three basic tissue systems are: dermal (epidermis), vascular (xylem and phloem) and ground or fundamental (parenchyma, collenchyma and sclerenchyma). Unlike animals, plants produce new tissues and organs all through their life by the activity of meristems. Meristems are located at the apices of shoots and roots. Cambium and cork cambium are lateral meristems.

The epidermis covers all the organs and is protective in function. The shoot and its organs often contain stomata in the epidermis through which gaseous exchange and water loss occur. Parenchyma is thin-walled and stores food reserves. Collenchyma and sclerenchyma provide mechanical strength to the plant organs.

Xylem is concerned with the conduction of water and minerals. The conducting cells of xylem consist of tracheids and vessels, which are dead at maturity and have lignified walls. Additionally, xylem may serve the function of support and storage of food reserves.

Translocation of food and other organic substances occurs in the phloem. In angiosperms phloem consists of sieve tube members, companion cells, parenchyma and fibres. Jute, flax and hemp are phloem fibres.

The primary tissues of the stem are derived from mitotic divisions, enlargement and differentiation of cells in the shoot apical meristem. They are: epidermis, cortex, endodermis, vascular tissue and pith. The vascular tissue occurs in the stem in bun-

dies. In dicotyledons, vascular bundles are arranged in a ring. In each bundle, phloem and xylem are located on either side of cambium. Increase in the amount of vascular tissues is contributed by cells divisions in cambium. The secondary tissues formed on the outside of cambium constitute phloem and those formed toward the inside constitute xylem or wood. Monocotyledons lack cambium.

The leaf epidermis bears numerous stomata. The chlorophyllous tissue between the upper and the lower epidermis is called mesophyll. The vascular bundles in the leaf occur in the midrib and veins.

The root apical meristem is covered by a root cap. The root cap cells produce a slimy mucilage which acts as a lubricant which helps the root tip to penetrate the soil. The root epidermis near the tip bears a large number of unicellular, short-lived hairs which absorb water and minerals. Below the epidermis lies a multilayered cortex, whose innermost layer differentiates into endodermis. The pericycle lies inner to endodermis and gives rise to lateral roots. Phloem and xylem in the root appear in separate bundles. In a root the xylem is exarch. Secondary growth occurs in the roots of most dicotyledonous plants.

Wood is actually secondary xylem. The wood of angiosperms has vessels (hardwood or porous wood); the wood of gymnosperms lacks them (softwood). In a log the outer, light-coloured living wood is called sapwood and the dark-coloured central core of dead wood is called heartwood. The secondary xylem formed during one growth season is called an annual ring.

Wood is the principal product of metabolism of trees and is an important renewable material for fuel, timber, paper pulp, rayon and plastics. Wood is easy to work with and can be made into a large number of articles.

## QUESTIONS

1. List the various functions of root.
2. What are the essential differences between annuals, biennials and perennials?
3. It is commonly believed that only roots develop below the ground. How would you prove that potato tuber is a stem and not a root?
4. What is the difference between a pinnately compound leaf and a branch bearing simple leaves?
5. Of what importance is the study of leaf morphology for a physiologist?
6. What are the three basic tissue systems in flowering plants? Name the tissues under each system.
7. What is a meristem? Where are meristems located in plants and what are their functions?
8. Distinguish between:
  - (a) Tracheid and vessel
  - (b) Sieve cell and sieve tube member
  - (c) Phellem and phelloderm
  - (d) Open bundle and closed bundle
  - (e) Fascicular cambium and interfascicular cambium
  - (f) Softwood and hardwood

9. A root system is extensively branched and bears a very large number of delicate root tips. How do the the root tips manage to penetrate the hard core of soil?
10. How is secondary thickening accomplished in stems of woody angiosperms? What is its significance?
11. What features make wood unique as a material?
12. Of what value is the study of plant anatomy?



## ABSORPTION AND MOVEMENT OF WATER IN PLANTS

PLANTS lose huge quantities of water through transpiration. The excessive water lost has to be replaced or else the plants will wilt. In multicellular land plants absorption of water occurs chiefly through the roots and the loss is mainly from the leaves. In this chapter, you will study how water moves from the soil into the plant and is ultimately lost as vapour.

The direction in which water will flow from one part of the plant to another or even from one cell to another cell, depends on the WATER POTENTIAL in the two regions. Water potential is measurable and is represented by the Greek letter  $\Psi$  (Psi).  $\Psi$  is usually measured in BARS (a bar being close to one atmosphere of pressure). Water moves from a region of high water potential to one of lower water potential.

Two factors which affect water potential are the amount of solutes, and external pressure. Pure water at atmospheric

pressure has zero water potential ( $\Psi=0$  bar). Addition of solutes causes lowering of water potential. Thus a 0.1M solution containing any solute has a  $\Psi$  of  $-2.3$  bars which is lower than the  $\Psi$  of pure water. When this solution is separated from pure water by a semi-permeable membrane, such as plasma membrane, ~~water~~ will move from the region of pure water to that of the solution. This process is called osmosis, about which you have learnt in Chapter 8. Water that occurs in soil contains dissolved minerals and is generally a weaker solution than the solution (consisting of protoplasm and vacuolar sap), present in root hairs. Therefore, water moves into the roots from the soil.

Contrary to the effect of solutes, pressure increases water potential. In a system consisting of a solution separated from water by a semi-permeable membrane, water movement can be prevented by applying pressure — OSMOTIC PRESSURE to the solution. The osmotic pressure is

balanced by the external pressure. In the case of 0.1 M solution this is equivalent to +2.3 bars.

You already know that when a plant cell is placed in a hypertonic solution, plasmolysis occurs due to loss of water and the cell becomes flaccid. What happens when a plant cell is placed in hypotonic solution? The cell absorbs water till it becomes turgid. As the protoplasm expands due to the entry of water it exerts a pressure on the elastic cell wall. This pressure is called **TURGOR PRESSURE**. You know from your physics lessons that every action causes an equal and opposite reaction. So in the case of plant cell, the elastic wall exerts a counter pressure. This is called **WALL PRESSURE**. When the wall pressure equals turgor pressure then the entry of water into the cell stops. At this stage the  $\Psi$  of the cell is equal to that of its environment. A dynamic equilibrium is reached in which there is no net movement, but equal exchange of water molecules can occur across.

**Turgidity of cells** is essential for plants to live and grow normally. Turgor pressure aids in cell enlargement and consequently in stretching of the stems and in keeping leaves erect and fully expanded. Thus turgid cells provide mechanical support necessary for the non-woody tissues (maize, sugarcane, banana, etc.). Loss of turgidity leads to wilting of leaves and drooping of shoots. You may have noticed that potted annual plants in your home and gardens wilt on a dry sunny day. This is because their cells become flaccid as more water is lost by transpiration, than is absorbed by the roots. This can be remedied by adequate watering. Even an unwatered potted plant recovers from wilting at night, as absorption continues to occur to make good the water lost from

foliage. The opening and closing of stomata are regulated by the turgidity of the guard cells. Leaf movements of many plants (like bean, sensitive plant *Mimosa pudica*) are controlled by loss and gain of cell turgor.

### Availability of Water in the Soil

Soil is the major source of water for land plants. Generally, soil is a combination of varying amounts of mineral particles and organic matter. It also contains water and air in the spaces between the particles. Water in the soil consists of three principal fractions: **GRAVITATIONAL WATER**, **CAPILLARY WATER** and **HYGROSCOPIC WATER**. When water enters the soil from the surface either by irrigation or rain, it passes through the spaces between the soil particles and reaches the **WATER TABLE** (depth below which the ground is saturated with water). This fraction of soil water is called **GRAVITATIONAL WATER**. It is not usually available to plants because it lies far below the reach of the roots. In the smaller pores of the soil, water is held

### IN SEARCH OF WATER

In the deserts, shallow rooted plants generally disappear after the rainy season and only perennials with deep extensive root systems are able to survive under extreme arid conditions. For example, a 60 cm high *Aerva persica* plant can have a tap root system reaching a depth of 6 metres. The desert grass *Lasiurus syndicus*, a native of Jaisalmer (Rajasthan) can send its roots to four metres depth. In *Welwitschia mirabilis*, an inhabitant of the deserts of South-West Africa, roots can penetrate to a distance of 18 metres.

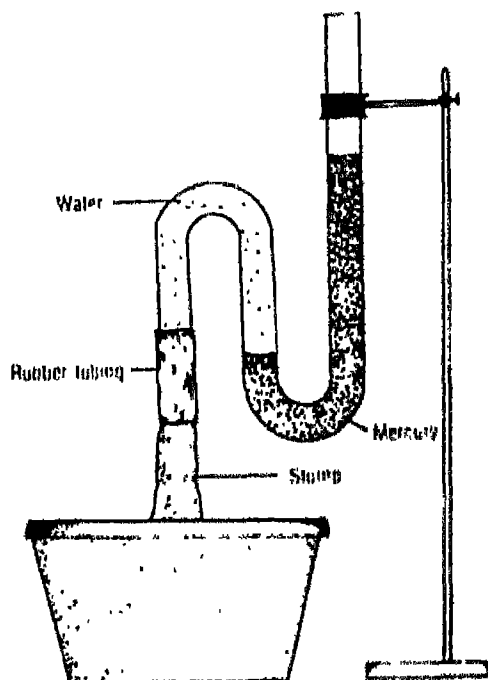
against the force of gravity by capillary forces and is called **CAPILLARY WATER**. This water is readily available to plants for absorption by roots. Even when the soil has lost its capillary water, the soil particles are covered by a thin film of water called **HYGROSCOPIC WATER**. This film of water is held by strong attractive forces between the soil particles and water molecules. These forces greatly reduce  $\Psi$  and therefore hygroscopic water is not available to plants.

### Absorption of Water by Plants

Scientists have shown that water can enter plants through its entire surface (leaves, stems and roots). However, the bulk of water is absorbed by land plants through the roots, especially at the tips. The root hairs provide a very large surface for water absorption. Movement of water from soil into the root hairs, and from them to cells of the xylem with lower water potentials, results in **ROOT PRESSURE** which pushes the water up the xylem vessels. The generation of root pressure is an active process. This is because only when minerals are accumulated against concentration gradient by active absorption using metabolically produced energy does the water potential of the surrounding cells become lowered to effect a net inward movement of water.

Can you believe that the total length of roots (minus root hairs) formed by a single rye plant (*Secale cereale*) in a period of four months is about 620 km, covering a total surface area of 255 sq metres? This is the astounding finding of Dr. Dittmer of Iowa State University.

**Activity:** Take a well-watered potted plant such as tomato. Cut off the stem close to the root. You will observe an exudation of the xylem sap from the stump. Fix a narrow glass tubing, containing coloured water on the stem with a piece of rubber tubing as shown in Fig. 27.1. After some



**Fig. 27.1** A set-up to measure root pressure  
time you will notice that the level of coloured water rises in the glass tube. This is the result of xylem sap being pushed upward by root pressure. Root pressure can also be measured by attaching a manometer to the cut stump with a rubber tubing. Pressures up to 5 atmospheres have been recorded by this method.

What is the maximum height to which root pressure can push water? While root pressure can account for transport of water to tips of herbaceous plants, it is

incapable of pushing up water to more than a few metres. Actively transpiring plants and tall trees, especially conifers do not generate root pressure. However, in herbaceous plants root pressure has another effect. When root pressure is high and transpiration is low, some plants may lose small quantities of liquid water in the form of drops from the margins or tips of leaves. This process is called GUTTATION. Guttation is frequently seen occurring at night in herbaceous plants growing under conditions of high soil moisture and high atmospheric humidity. Guttation occurs through specialised pores called HYDATHODES situated near a vein ending (Fig.27.2).

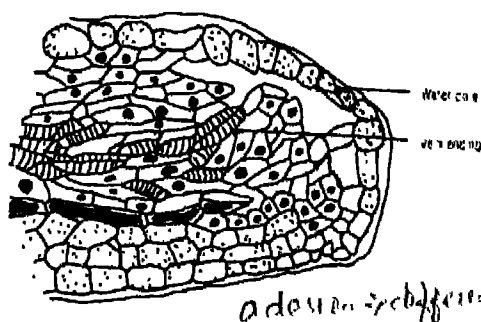


Fig. 27.2 Longitudinal section of a leaf tip showing a hydathode

Some of the tallest trees in the world reach heights of over 80 metres. Their roots cover an extensive area in the soil to absorb water. How is water pumped to such great heights? This is one of the most challenging questions which biologists have tried to answer for the past 250 years. In explaining the ascent of water, several physical phenomena, the chemical nature of plant cell walls and the structure of the xylem tissue have to be kept in mind. The enormous number of moist walls of mesophyll cells lose water vapour which accumulates in the intercel-

lular spaces and makes them highly saturated. The intercellular spaces in the mesophyll of leaves are connected to the atmosphere through the stomata. The air outside is comparatively dry. Since dry air has a lower water potential than moist air, water vapour diffuses out through the stomata. This lowers the water potential of the surrounding mesophyll cells, which then draw water from the cells in the deeper tissues of the leaf. Thus during transpiration (the process by which leaves lose water vapour from the aerial parts) water is drawn continuously from the tip of the tree, along the xylem of the stem and the root tips in contact with soil water to create a TRANSPIRATION PULL.

The walls of xylem vessels made of ligno-cellulose have a strong affinity for water molecules. The adhesion of water molecules to the xylem vessels, and cohesion of water molecules, both by hydrogen bonds, together help to form thin, unbroken columns of water in the capillaries of xylem vessel elements. When the transpiration pull is exerted, a negative pressure or TENSION is generated in the xylem, which is transmitted down to the roots. Just as an increase of pressure results in increased water potential, so does tension cause a decrease in water potential. The lowered water potential favours uptake of water by roots. The above mechanism can account for lifting water to the tips of the tallest trees that occur on the earth. Water potential as low as  $-30$  bars has been measured in the leaves borne on tree tops. Low water potential of this magnitude is sufficient to overcome gravitational pull and resistance offered by the narrow capillaries of xylem vessels.

### Transpiration

Land plants absorb large quantities of



water from the soil, but only a fraction of it is utilised for maintenance of their life. The rest of it is lost from the plant either in the form of liquid or vapour.

#### HOW MUCH WATER DOES A PLANT NEED ?

Less than 2 per cent of all the water that a plant absorbs is required for its various uses. Miller (1938) estimated the water budget of a Kansas maize plant (*Zea mays*) as follows:

Water occurring as a constituent	1,872 g
Water used as a reagent	250 g
Water lost in transpiration	202,106 g
	204,228 g

About 98 per cent of the water absorbed by land plants evaporates from the aerial parts of the plant and diffuses into the atmosphere. It is understandable that transpiration largely occurs through the minute pores called stomata (about which you learned earlier) in the leaves, which are thin and expose an enormous surface.

#### Role of Stomata in Transpiration

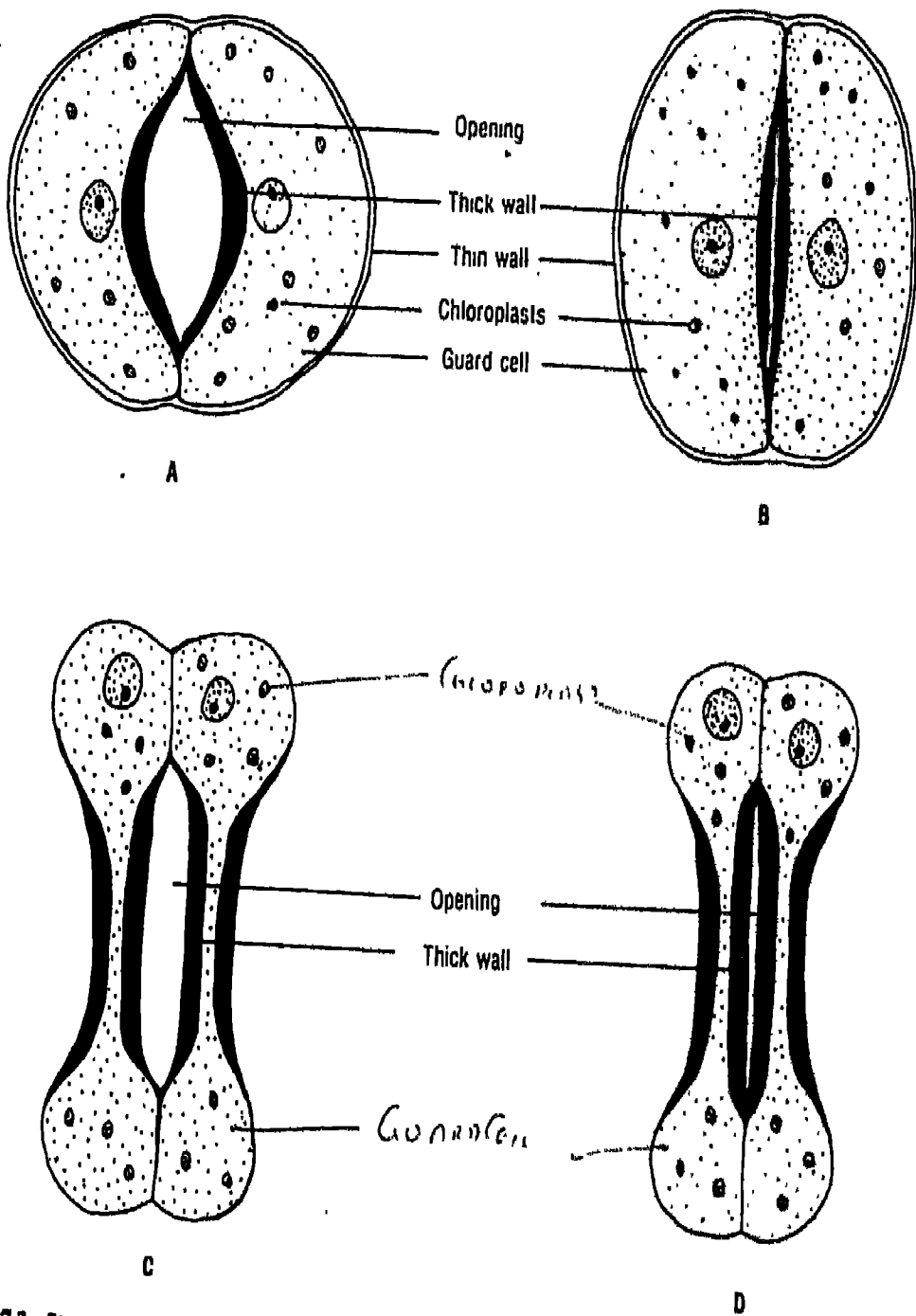
As stomata are the gateways of transpiration, their behaviour influences the rate of transpiration. Stomata are generally closed at night and during the later part of a hot sunny afternoon. The rate of transpiration is generally very low at night, increases rapidly from early morning until midday and then decreases rapidly. Such a diurnal variation in transpiration is regulated by the degree of opening of the stomata.

Let us examine the structure of stomata and the mechanism of their opening and closing. As you studied earlier, each stoma is a small aperture in the epidermis sur-

rounded by two guard cells. The opening and closing of the stomata are controlled by the size and shape of guard cells, resulting from the changes in their turgor. In dicotyledonous plants such as bean and tobacco, the guard cells are usually kidney-shaped (Fig.27.3). The guard cell walls surrounding the aperture are thicker than the outer wall. When the guard cells become turgid, the outer walls become more convex, drawing the inner walls apart and increasing the size of the stomatal pore (Fig.27.3A). When the turgor pressure of the guard cells decreases, the inner walls sag, causing closure of the space between them (Fig.27.3B). In grasses, the guard cells are dumbbell-shaped and their cell walls are thickened only in the middle. When the guard cells expand by water intake, their ends with thin walls bulge outwards and draw the thick walls apart. This results in stomatal opening (Fig.27.3C). When the guard cells lose water, the thick walls move closer and the opening is shut (Fig.27.3D). That distension of guard cells is responsible for opening stomata is well-known but the mechanism by which water moves into the guard cells has been explained convincingly only recently.

It has been demonstrated that changes in turgor pressure that open and close the stomata result from the reversible absorption and loss of potassium ions ( $K^+$ ). The stomata open when the guard cells take up  $K^+$  from the surrounding cells. This causes a decrease in the water potential within the guard cells. Water enters and causes the guard cells to become turgid.

The uptake of  $K^+$  ions is balanced by one of the following: (i) uptake of chloride ( $Cl^-$ ), (ii) transport of  $H^+$  ions released from organic acids (such as malic acid), (iii) by the negative charges of the



**Fig. 27.3** Stomatal opening and closing  
 A,B. stomata from a dicotyledonous leaf; C,D. stomata from a monocotyledonous (grass) leaf. In A and C, guard cells are turgid and the stoma is open. In B and D, guard cells are flaccid and the stoma is nearly closed.

organic acids when they lose  $H^+$  ions. The exodus of  $K^+$  ions leads to osmotic loss of water from the guard cells and the closure of stomata.

There are several factors that influence stomatal closure. Some plants show rhythms of opening and closing of stomata irrespective of the environmental conditions.

Severe drought stress or intense solar radiation causes the production of a plant hormone, ABSCISIC ACID (ABA) which signals the closure of stomata. This has an adaptive value in preventing excessive water loss.

#### *Factors Affecting Transpiration*

Two individual plants grown in the same environment may lose different amounts of water by transpiration. This is largely due to differences in their total leaf area. However, the rate of transpiration per unit area of the leaf surface may also differ, based on the morphology and anatomy of the leaves. For example, plants growing in arid regions bear small leaves with thick cuticle, sunken stomata, epidermal hairs and well-developed palisade parenchyma. There are also plants in which leaves are absent. The succulent stems take up the photosynthetic function and contain mucilage or latex in their tissues. These features help reduce the water loss from plants. The rate of transpiration also depends upon the extent of root and shoot growth. Usually the rate of transpiration increases with an increase in the root-shoot ratio.

Transpiration is influenced by environmental factors such as light, temperature, atmospheric humidity (vapour pressure), wind and availability of water in the soil. As explained earlier, light influences transpiration through its effect on the opening

of the stomata. Leaves absorb sunlight as radiant energy. Only a small proportion of it is used in photosynthesis and the rest of it is converted into heat energy which increases the temperature of the leaf. A relative rise in temperature of the leaf increases the vaporisation of water within the leaf, causing rapid water loss from the leaf through transpiration. The rate of evaporation of water is generally doubled with about every  $10^\circ C$  rise in temperature. A decrease in the amount of available water in the soil reduces absorption and hence transpiration. WILTING occurs when the loss of water by transpiration exceeds the rate of uptake by roots.

The diffusion of water vapour from the intercellular spaces of leaves to outside atmosphere depends on the moisture content of the atmosphere. If the moisture content of the atmosphere is high, the rate of transpiration is relatively low but as the moisture in the air decreases, the rate of transpiration increases rapidly.

The movement of air (wind) over the transpiring leaf surface tends to remove water vapour diffused from the leaf and in turn increases the water vapour gradient from the leaf to the outside air. High wind velocities often induce stomatal closure due to rapid water loss from the guard cells causing a decrease in transpiration. At times, moderate wind also reduces leaf temperature which in turn decreases the rate of transpiration. This usually occurs on a sunny day when the leaf temperature is higher than that of the surrounding atmosphere.

#### *Significance of Transpiration*

Transpiration is important for plants because it directly influences the absorption of water from the soil. The evaporation of water during transpiration contri-

butes to the cooling of leaves (and also the surrounding air) and protects leaves from heat injury, particularly under conditions of high temperature and intense sunlight. Transpiration is also important because it causes the movement of water and miner-

als absorbed by the roots to the other parts of the plant. Leaves are ideally suited to capture sun's energy and absorb carbon dioxide through the stomata. These features tend to increase transpiration rates.

The rate of transpiration in a plant is an indirect measure of the rate of photosynthesis, as it indicates the degree and period of stomatal opening. The amount of water used by a crop plant to produce a unit weight of dry matter is called water requirement. Water requirement differs from crop to crop. Rice, sugarcane, and tomato require large amounts of water. Bajra, sorghum and ragi (*Eleusine coracana*) require relatively low inputs of water. In a country like India where irrigation is not available in large tracts of land, the choice of crops that can be raised under rainfed conditions is largely determined by water requirement. The same is true of plantation and tree crops. Coffee, tea, arecanut, coconut, rosewood, teak, willow and bamboos need large quantities of water. Neem, acacias and *Prosopis*, sisham (*Dalbergia sissoo*) can grow well with low moisture. In general, plants that occur naturally in arid regions with adaptations to reduce transpiration also show slow rates of growth.

#### ANTI-TRANSPIRANTS

You have studied earlier that most of the water absorbed by plants is lost to the atmosphere by transpiration and hence the water use by plants is very inefficient. At present efforts have been made to improve the efficiency of water use by plants. One of the approaches is to reduce transpiration by the application of certain chemical substances which increase leaf-resistance to water vapour diffusion without affecting carbon dioxide uptake. These substances are called anti-transpirants. (1) Phenylmercuric acetate causes partial closure of stomata. (2) Waxy materials that cover the stomata as a film have more resistance to water vapour than to carbon dioxide. These substances are commonly used as anti-transpirants. The use of anti-transpirants to reduce the enormous loss of water by transpiration has practical importance to improve plant productivity under conditions of limited water supply.

(2) 4 ABA ↑

#### SUMMARY

Water is the principal constituent of plants and is essential for the maintenance of life, growth and development. Plants absorb water from the soil through their roots, transport it to other parts of the plant through the xylem and lose it into the atmosphere by transpiration. Hence, there is a soil-plant-atmosphere continuum of

water. Various physical phenomena such as diffusion, osmosis, turgor and cohesion-tension play a role in the absorption of water from the soil and its transport within the plants. The upward movement of water in plants is mainly through the forces of cohesion between water molecules and adhesion between the water and the walls of the xylem cells.

The bulk of water absorbed by plants is lost from leaves into the atmosphere as vapour by the process called transpiration. Since stomata are the openings through which water is lost from plants, transpiration is mainly controlled by stomatal movements. The opening and closing of stomata depend on changes in the turgor of guard cells. The turgidity of guard cells is regulated by  $K^+$  fluxes between them and the surrounding epidermal cells.

Transpiration is also influenced by environmental factors such as light, temperature, availability of soil water and atmospheric humidity. Transpiration facilitates the movement of water and minerals, absorbed by roots, to other aerial parts of the plant. The water requirement of crops principally determines their cultivation in various agro-climatic zones. Plants growing in areas of severe water scarcity have various adaptations to minimise water loss.

## QUESTIONS

1. What are the two kinds of interactions of water molecules that allow water to travel upward in plants? What other physical process aids in water transport to tops of trees?
2. Which of the following has the highest water potential (a) 1M salt solution (b) 1M sugar solution (c) distilled water (d) 1M sugar solution with 2.3 bars pressure applied to it.
3. Fill in the blanks:
  - (a) The water potential of pure water is \_\_\_\_\_
  - (b) When plant absorbs the water from the soil, the water potential of the root cell is \_\_\_\_\_ than the soil.
  - (c) Plants lose water by the processes of \_\_\_\_\_ and \_\_\_\_\_
  - (d) Loss of water through the epidermis of aerial parts of the plant is reduced by \_\_\_\_\_
4. What forces are involved in the absorption of water from the soil by root hairs?
5. Define osmosis and explain how it influences other components of cell water relations in plants.
6. What are guard cells? Explain their role in regulating transpiration.
7. Why is transpiration in higher plants considered a necessary evil?
8. Write brief explanatory notes on (a) Root pressure (b) Water potential (c) Guttation and (d) Significance of transpiration.



## MINERAL AND NITROGEN NUTRITION IN PLANTS

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### Modes of Plant Nutrition

ALL living organisms require raw materials for building their structure and for maintaining their functions. The chemical substances that provide nourishment to living organisms are called **NUTRIENTS**. Nutrients may be simple or complex organic molecules or mineral ions. For example, green plants utilise water and carbon dioxide to form sugar during photosynthesis. Further conversion of sugars into starch, cellulose, fats, amino acids and other complex organic molecules requires the participation of inorganic molecules and ions. Nitrogen and sulphur are taken up in the inorganic form and are reduced and converted into organic molecules such as amino acids. Iron is used by plants to synthesise cytochromes. You have already studied that some enzymes require metals as cofactors.

#### *Heterotrophic Nutrition*

In the classification of living organisms

you have learnt that the kingdom Plantae is characterised by autotrophic mode of nutrition. However, some plants are incapable of photosynthesis and obtain water, minerals and certain organic compounds from other autotrophs. This type of nutrition is referred to as **HETEROTROPHIC NUTRITION**. For example, the parasitic plant *Cuscuta* grows on green host plants and sends out root-like structures, called **HAUSTORIA**, which penetrate the vascular tissue of the host and absorb water, minerals and organic compounds.

Some autotrophs supplement their nutritional requirements by trapping and digesting insects and other small animals. Such plants are called **CARNIVOROUS** or **INSECTIVOROUS PLANTS** (Fig. 17.13). The best known examples of insectivorous plants are the pitcher plants [*Nepenthes* (Fig. 28.1), *Sarracenia*], the sundew (*Drosera*), venus fly trap (*Dionaea*) and the bladderwort (*Utricularia*). *Nepenthes*

pitcher.

The sundew plant (*Drosera*) has rosettes of leaves covered with hairs that secrete drops of a sticky fluid at their tips (these glisten in light and hence the name 'sundew'). An insect alighting on the leaf gets stuck and the other hairs bend down and prevent the insect from escaping. The enzymes secreted by the hairs digest the insect and the products are absorbed by the leaf surface. Research has shown that many insectivorous plants are able to survive without feeding on the insects but their growth is stimulated when they trap and utilise insects.

### *Inorganic Nutrition in Plants*

Chemical analysis shows that carbon, oxygen, hydrogen and nitrogen constitute the bulk of the plant body. In addition, a large number of other elements are also found. Some of these occur in trace amounts (Table 28.1).

Fig. 28.1 In the pitcher plant *Nepenthes*, leaf is modified to trap insects.

*Nepenthes*, which has large pitchers, occurs in north-eastern India and has been listed as an endangered plant. Pitcher plants (Fig 28.1) bear pitcher-shaped leaves that collect small amounts of water. Insects are attracted to these pitchers either by their bright colours or by their nectar. The insects that slip into water are prevented from coming out by the hairs near the rim of the pitcher, which are pointed downwards. The trapped insects eventually die and are decomposed by microorganisms. The breakdown products of insects are absorbed by the inner surface of the

Table 28.1  
ELEMENTAL COMPOSITION OF MAIZE  
PLANTS BASED ON THE DRY WEIGHT

Element	% of dry weight
Oxygen	44.4
Carbon	43.6
Hydrogen	6.2
Nitrogen	1.5
Silicon	1.2
Potassium	0.92
Calcium	0.23
Phosphorus	0.20
Magnesium	0.18
Sulphur	0.17
Aluminium	0.10
Iron	0.08
Manganese	0.04

Data from Latshaw and Miller (1924)



### *Criteria of Essentiality of Elements*

The roots of green plants absorb a very large number of elements from the soil. This number may vary from 30 to 40. But only a few of them are essential for plant life. How is it possible to determine which elements are essential for plant growth and development? Our answer to this question has been based on water culture experiments (see the box). The following are the criteria of essentiality of elements: (i) the element must be absolutely necessary for supporting normal growth and reproduction, (ii) the requirement of the element must be specific and not replace-

able by another element, (iii) the element must be directly involved in the nutrition of the plant. Magnesium, for example, is a constituent of the chlorophyll molecule and is essential for photosynthesis. It cannot be replaced by any other element for the same function. It is also required as a cofactor by many enzymes involved in cellular respiration and other metabolic pathways. Similarly, iron is a constituent of cytochromes.

The essential elements are divided into two categories based on the quantity in which they are required by plants: MACROELEMENTS and MICROELEMENTS.

### SOIL-LESS CULTURE OR HYDROPONICS

In general, soil supplies the mineral nutrients for plant growth. However, to determine what elements are essential for plant growth, and what symptoms are produced by the absence or deficiency of an essential element a well-defined nutrient medium has to be used. For this purpose seedlings are grown in highly washed pure sand in a glass, glazed porcelain or plastic container, and supplied with a carefully made-up nutrient solution. Only pure salts and glass distilled water should be used. Care must be taken to exclude organic matter, microbial contaminants and dust. If the seeds have large cotyledons or endosperm these must be removed before the seedlings are planted. Cultivation of plants by placing the roots in the nutrient solution is called HYDROPONICS. It is necessary to aerate the solution to provide roots with adequate oxygen.

By excluding a particular element in a culture solution, characteristic deficiency symptoms can be observed. Deficiency symptoms may vary from species to species. The results obtained from soil-less culture may then be used to determine deficiencies under field conditions, and suitable ameliorative measures may be taken.

The earliest experiment using a culture solution was done by Sachs in 1860 and he showed the essentiality of nitrogen for plant growth. Another early worker in the study of mineral nutrition was Knop (1865). His prescription for preparing a nutrient solution was used for a long time by other researchers. The role of micronutrients was not known then and the medium contained only macronutrients. Almost seventy years later Arnon and Hoagland's medium was formulated. This contained micronutrients. Iron was supplied as ferrous sulphate, and often it precipitated out. This problem has now been solved by dissolving the ferrous sulphate along with a chelating agent Na-EDTA (disodium salt of ethylene-diaminetetraacetic acid).

# FORMULAE OF TWO NUTRIENT MEDIA

Knop (1865)	g/l
$\text{KNO}_3$	0.2
$\text{Ca}(\text{NO}_3)_2$	0.8
$\text{KH}_2\text{PO}_4$	0.2
$\text{FePO}_4$	0.1
Arnon and Hoagland (1940)	g/l
$\text{KNO}_3$	1.02
$\text{Ca}(\text{NO}_3)_2$	0.492
$\text{NH}_4\text{H}_2\text{PO}_4$	0.23
$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	0.49 mg/l
$\text{H}_3\text{BO}_3$	2.86
$\text{MnCl}_2 \cdot 4\text{H}_2\text{O}$	1.81
$\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$	0.08
$\text{SnSO}_4 \cdot 7\text{H}_2\text{O}$	0.22
$\text{H}_2\text{MOO}_4 \cdot \text{H}_2\text{O}$	0.09
$\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ 0.5% } Tartaric acid 0.4% }	0.6 ml/l 3 x weekly

Macroelements must generally be present in plant tissues in concentrations of at least one milligram per gram of dry matter. Example: carbon, hydrogen, oxygen, nitrogen, phosphorus, sulphur, potassium, calcium, magnesium and iron. Microelements are needed in very small amounts. Manganese, copper, molybdenum, zinc, boron and chlorine have been

established as essential microelements. Recent research has shown that a few other elements such as cobalt, vanadium, silicon and nickel may be essential for certain plants.

It is important to recognise that sodium and iodine, which are essential for animals, are not needed by the majority of plants.

### Sources of Essential Elements for Plants

All elements incorporated into plants are ultimately derived from the atmosphere, water and soil (Table 28.2). Carbon enters a plant as atmospheric carbon dioxide, while hydrogen is obtained mainly from water. Oxygen can come from the air, or from water and in the form of inorganic ions.

Atmospheric nitrogen, which occurs in abundance, is inert and most plants are unable to use it. You have learnt of the atmospheric activities by which nitrogen combines with oxygen and is brought down by rain to the soil. There are also certain highly specialised organisms

called NITROGEN FIXERS. These organisms, occurring in the soil, convert nitrogen gas ( $N_2$ ) to anionic forms such as nitrate ( $NO_3^-$ ) or nitrite ( $NO_2^-$ ) or a reduced cationic form such as ammonium ( $NH_4^+$ ). These compounds enter plants as nutrients through the root and are assimilated as organic nitrogen. The plants, in turn, provide organic nitrogen to heterotrophic organisms. All other inorganic elements needed by plants are absorbed from the soil which is ultimately derived from the parent rocks by weathering. Hence, these inorganic elements are called MINERAL ELEMENTS. Non-mineral elements include carbon, oxygen and hydrogen.



Fig. 28.2 Symptoms of boron deficiency in cauliflower. Left Lesions in the pith of stem. Right. The head (curd) and part of the root system have died. (Photo: VEG Gustav Fischer Verlag, Jena)

Table 28.2

## ROLES OF MINERAL ELEMENTS IN PLANTS

<i>Element</i>	<i>Obtained as</i>	<i>Regions of plant in which required</i>	<i>Functions</i>	<i>Deficiency symptoms</i>
Nitrogen	$\text{NO}_3^-$ , $\text{NO}_2^-$ or $\text{NH}_4^+$	Everywhere particularly in meristematic tissues	Constituent of proteins, nucleic acids, vitamins, hormones, coenzymes, ATP, chlorophyll	Stunted growth, chlorosis
Phosphorus	$\text{H}_2\text{PO}_4^-$	Younger tissues, withdrawn from older, metabolically less active cells	Constituent of cell membrane; certain proteins; all nucleic acids and nucleotides; required for all phosphorylation reactions	Poor growth, leaves dull green
Potassium	$\text{K}^+$	Meristematic tissues; buds, leaves, root tips	Helps determine anion-cation balance in cells; involved in protein synthesis; involved in formation of cell membrane and in opening and closing of stomata; increases hardiness; activates enzymes and helps in maintenance of turgidity of cells	Yellow edges to leaves; premature death
Calcium	$\text{Ca}^{2+}$	Meristematic and differentiating tissues; accumulates in older leaves	Involved in selective permeability of cell membranes; activates certain enzymes; required for development of stem and root apex, and as calcium pectate in the middle lamella of the cell wall	Stunted growth
Magnesium	$\text{Mg}^{2+}$	Leaves; withdrawn from ageing leaves and exported to developing seeds	Activates enzymes in phosphate metabolism; constituent of chlorophyll; maintains ribosome structure	Chlorosis

<i>Element</i>	<i>Obtained as</i>	<i>Regions of plant in which required</i>	<i>Functions</i>	<i>Deficiency symptoms</i>
Sulphur	$\text{SO}_4^{2+}$	Stem and root tips; young leaves; remobilised during senescence	Constituent of certain proteins, vitamins (thiamine, biotin, CoA) and ferredoxin	Chlorosis
Iron	$\text{Fe}^{3+}$	Everywhere; collects along leaf veins	Constituent of ferredoxin and cytochromes; activates catalase; required for synthesis of chlorophyll	Chlorosis
Manganese (trace)	$\text{Mn}^{2+}$	Leaves and seeds	Activates certain enzymes (carboxylases)	Chlorosis; grey spots on leaves
Molybdenum (trace)	$\text{MO}^{3+}$ or $\text{MO}^{4+}$	Everywhere; $\text{MO}^{3+}$ particularly in roots	Activates certain enzymes in nitrogen metabolism	Slight retardation of growth
Boron (trace)	$\text{BO}_3^{3-}$ or $\text{B}_4\text{O}_7^{2-}$	Leaves and seeds	Required for uptake and utilisation of $\text{Ca}^{2+}$ ; pollen germination and cell differentiation, carbohydrate translocation	Brown heart disease
Copper (trace)	$\text{Cu}^{2+}$	Everywhere	Activates certain enzymes	Dieback of shoots
Zinc (trace)	$\text{Zn}^{2+}$	Everywhere	Activates various enzymes especially carboxylases, part of carbonic anhydrase and various dehydrogenases; needed for auxin synthesis	Malformed leaves
Chlorine	$\text{Cl}^-$	Everywhere	With $\text{Na}^+$ and $\text{K}^+$ helps determine solute concentration and anion-cation balance in cells; essential for oxygen evolution in photosynthesis	

Nitrogen is unique as it is derived from both mineral and non-mineral sources.

### Functions of Inorganic Elements

The inorganic elements required by higher plants and their role are listed in Table 28.2. The most important use of inorganic elements is in the synthesis of various chemical compounds essential for plant growth. For example, nitrogen is an essential component of all amino acids, proteins, nucleic acids, chlorophyll, auxins, cytokinins and vitamins. Calcium is a constituent of calcium pectate of the middle lamella which binds adjacent cells to each other. Some enzymes are also activated by mineral elements. Magnesium is an essential part of the chlorophyll molecule. It also activates certain enzymes. Sulphur is a constituent of some essential amino acids (methionine and cysteine) and some proteins. Phosphorus is a constituent of many important organic compounds such as ATP, NAD, NADP, DNA, RNA and phosphorylated sugars and lipids.

The second major role of mineral elements such as calcium, magnesium, manganese, chlorine, sodium and potassium is to serve as cofactors of enzymes. Among these potassium is most effective. Over 40 enzymes depend on potassium for optimum activity. Potassium is also involved in the translocation of organic substances in the phloem.

Minerals also play several other roles in plants. They influence the absorption of water by cells and affect the degree of permeability of cell membranes. For example, sodium increases membrane permeability whereas calcium decreases it.

### Symptoms of Mineral Deficiency in Plants

When plants lack the required quantities

of one or more essential elements, they show poor growth and develop specific **DEFICIENCY SYMPTOMS**. These have been called 'hunger signs' by plant scientists. In a cultivated field or an orchard, these symptoms can be used to detect the type of mineral deficiency and take appropriate ameliorative measures. Certain plants which rapidly develop characteristic deficiency symptoms for particular elements can be used as indicator plants for testing the soils. The most common and striking types of mineral deficiency symptoms include stunted growth, chlorosis (yellowing of leaves in various distinctive patterns), dieback of shoots (death of shoot meristems), death of tissues (necrosis) (Fig. 28.2) and poor reproductive development. Excessive amounts of essential elements are toxic to plants and may induce characteristic symptoms which may lead to their detection.

### Uptake of Mineral Nutrients

Roots take in some mineral nutrients selectively, including some which may not be essential for them. Thus the ash analysis of a plant does not always indicate what elements are essential. The process of intake of nutrients from the soil is called **ABSORPTION**. Plants absorb minerals from the soil through the root by two ways: (i) passive absorption and (ii) active absorption.

#### Passive Absorption

In most cases, the movement of mineral ions into the root occurs by **DIFFUSION**. You may recall that diffusion has been discussed in Chapter 8. Molecules or ions diffuse from a region of their higher concentration to a region of their lower concentration. As these substances diffuse, they exert a pressure called **DIFFUSION**

**PRESSURE.** The movement of mineral ions into root cells as a result of diffusion is called **PASSIVE ABSORPTION**.

### *Active Absorption*

The uptake of mineral ions against concentration gradient is called **ACTIVE ABSORPTION**. As you have studied earlier, such movement of minerals requires an expenditure of energy by the absorbing cells. This energy is derived from respiration and is supplied through ATP. When the roots are deprived of oxygen, they show a sudden drop in active absorption of minerals. The mineral ions accumulated in the root hairs pass into the cortex and finally reach the xylem. The minerals in the xylem are then carried along with water to other parts of the plant along the transpiration stream. Mineral elements brought to the leaves are subsequently assimilated into organic molecules and are redistributed to other parts of the plant through the phloem.

### **Nitrogen Nutrition in Plants**

Atmosphere is the ultimate source of nitrogen. Nitrogen is a highly inert gas. It cannot be used directly but has to be fixed i.e. combined with C, H, N, O to form compounds. As already explained, higher plants utilise nitrogen in the oxidised forms such as nitrate ( $\text{NO}_3^-$ ) and nitrite ( $\text{NO}_2^-$ ) or in the reduced form ( $\text{NH}_4^+$ ) made available to plants by the nitrogen fixers. The best known nitrogen-fixing symbiotic bacterium is *Rhizobium*. This bacterium lives in soil to form root nodules in plants belonging to the family Leguminosae such as beans, gram, groundnut and soybean. Root nodules are little outgrowths on roots. When a section of the root nodule is examined, it appears pinkish due to the presence of a pigment

called **LEGHEMOGLOBIN**. This pigment is closely related to **HEMOGLOBIN**, the red pigment of human blood. Like hemoglobin, leghemoglobin is an oxygen scavenger. The enzyme that catalyses the fixation of nitrogen (nitrogenase) functions under anaerobic conditions. Leghemoglobin combines with oxygen and protects **NITROGENASE**.

Free living microorganisms such as the cyanobacteria and photosynthetic bacteria can also fix nitrogen. Some cyanobacteria also have symbiotic association with plants. They are found in lichens, *Anthoceros* (a liverwort), fronds of *Azolla* (a water fern) and roots of *Cycas* (a gymnosperm).

### *Process of Biological Nitrogen Fixation*

In the process of biological nitrogen fixation, the dinitrogen molecule is progressively reduced by the addition of pairs of hydrogen atoms (Fig. 28.3). Finally, the three bonds between the two nitrogen atoms are cleaved and ammonia is formed. These reactions occur only in the presence of a single enzyme called **NITROGENASE** (Fig. 28.3). The process of nitrogen fixation requires a strong reducing agent and ATP to transfer hydrogen atoms to dinitrogen. Depending on the type of nitrogen fixer, either respiration or photosynthetic metabolism may provide the necessary ATP and the reducing agent. Ammonia formed in the process of biological nitrogen fixation is subsequently used for the synthesis of amino acids. These amino acids may be transported through phloem to other parts of the plant where they are needed.

The free-living nitrogen fixers (refer to chapter 22) convert nitrogen gas into ammonia ( $\text{NH}_3$ ) or ammonium ions in the soil. Ammonia is toxic to plants but

Molecular nitrogen

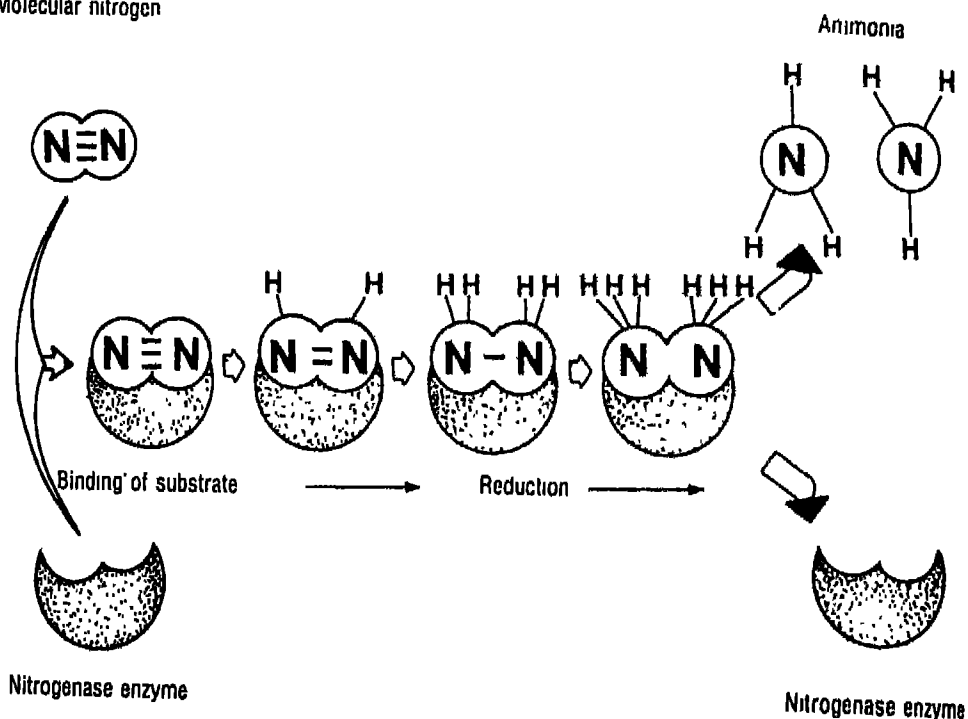


Fig.28.3 A schematic diagram to show progressive reduction of one molecule of nitrogen in the presence of nitrogenase enzyme to yield two molecules of ammonia

ammonium ions can be taken up safely by higher plants. However, flowering plants are more adapted to absorb nitrate ( $\text{NO}_3^-$ ) than ammonium ions ( $\text{NH}_4^+$ ) from the soil as a source of nitrogen. In such a case where do the nitrate ions in the soil come from? Here again, plants depend upon specific soil bacteria which convert ammonia to nitrate. Soil bacteria such as *Nitrosomonas* and *Nitrosococcus* which live in soil are capable of converting ammonia to nitrite ( $\text{NO}_2^-$ ) ions. *Nitrobacter* oxidises nitrite to nitrate. This process of converting ammonia into nitrate, a form of nitrogen more available to plants, is called **NITRIFICATION**. The nitrifying bacteria are

**CHEMOAUTOTROPHS** and they derive energy from oxidation of ammonia or nitrate for the synthesis of their own organic food.

#### *Nitrate Assimilation in Plants*

The process of nitrate reduction to ammonia is accomplished by two steps mediated by two specific enzymes. First the nitrate is reduced to nitrite by an enzyme called **NITRATE REDUCTASE**. This enzyme is a flavoprotein and contains molybdenum. The nitrate ions are then reduced to ammonia by an enzyme called **NITRITE REDUCTASE**. Ferredoxin is the most direct source of electrons for nitrite reduction and hence it occurs specifically in leaves.



Therefore, nitrite ions formed in other parts of the plant are transported to leaves and further reduced to ammonia. Nitrite reductase does not require molybdenum but may contain copper and iron.

#### Application of Fertilisers

Soils normally contain sufficient quantities of essential minerals. However, three important elements need to be replenished in crop fields as they are depleted by repeated cultivation. These fertiliser elements are nitrogen, phosphorus and potassium — abbreviated as NPK. The common sources of these elements used in

India are: nitrate of soda, ammonium sulphate, ammonium nitrate, ammonium chloride, urea, calcium ammonium nitrate, superphosphate, bonemeal, rock phosphate and calcium magnesium phosphate. The NPK fertilisers comprise nitrophosphate with potash in varying proportions. Bags of fertilisers are labelled 17-18-9 or 15-15-15 or other combinations. These numbers refer to the percentage by weight of nitrogen, phosphorus and water soluble potassium. The dosages vary according to the crop, soil, season and other climatic conditions.

## SUMMARY

Plants derive inorganic nutrients from soil, water and atmosphere. Some green plants supplement their nutritional requirement by parasitic and insectivorous habit. A few plants are totally parasitic on other green plants for all their requirements. Although plants may absorb a wide range of inorganic elements, only a few are essential for their normal growth and reproduction. Plants require some essential elements in higher quantities (macroelements) and others in lower amounts (microelements). Some essential elements form structural components and others participate in biochemical reactions and serve as cofactors for several enzymes. NPK are the three main mineral elements supplied to crops as chemical fertilisers. Deficiency or absence of an essential element leads to reduction in growth, chlorosis, necrosis and other characteristic symptoms. The essential elements enter a plant from the soil through the root by active or passive absorption. The absorbed elements are then transported from the root to other parts of the plant through the xylem.

Atmospheric nitrogen is inert and cannot be used directly by plants. The conversion of atmospheric nitrogen to usable nitrogen compounds is processed primarily by certain nitrogen fixing bacteria and cyanobacteria. Some of these are free-living in the soil and others such as *Rhizobium* are associated symbiotically with the roots of higher plants. In nitrogen fixation the dinitrogen of the atmosphere is reduced to ammonia with the help of enzyme nitrogenase. This process requires a strong reducing agent and ATP. Ammonia is the main product of biological nitrogen fixation in the soil and is usually converted to nitrates by another group of bacteria. Nitrate is absorbed by plants, with the help of two enzymes — nitrate reductase and nitrite reductase — and is reduced to ammonia. Ammonium ion is subsequently incorporated into the amino acids and other nitrogenous compounds in the plant.

Fertilisers are chemical compounds used to replenish minerals in crop fields. The

## QUESTIONS

1. Tick (✓) the correct answers in each of the following:

(a) The mineral constituent of the cell wall is

- (i) iron
- (ii) magnesium
- (iii) potassium
- (iv) calcium

(b) Active uptake of minerals by roots mainly depends on the

- (i) availability of oxygen
- (ii) light
- (iii) temperature
- (iv) availability of carbon dioxide

(c) In nitrogen fixation

- (i) plants convert atmospheric nitrogen to nitrates
- (ii) plants absorb ammonia from the soil
- (iii) the bacteria are all housed in nodules on the plant's roots.
- (iv) the enzyme nitrogenase produces ammonia from gaseous nitrogen.

2. Match the words in Column I with the phrases in Column II

*Column I*

- a. Magnesium
- b. Sulphur
- c. Calcium
- d. Iodine
- e. Manganese

*Column II*

- i. found in middle lamella
- ii. a structural component of chlorophyll
- iii. required for enzyme activity
- iv. found in some amino acids
- v. a component of sugars
- vi. not important for plants

3. Which are the two macronutrients that usually play the most important role in limiting plant growth globally?
4. If you grow a potted plant that initially weighed 200g and eventually weighed 50 kg, would you expect the soil in the pot to change weight? Explain.
5. How would you determine whether or not a particular element is essential for plants?
6. Write explanatory notes on (a) Micronutrients, (b) Biological nitrogen fixation, (c) Insectivorous plants.
7. List the macronutrients and mention their major function.
8. What are the indications for mineral deficiency in plants?

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**PHOTOSYNTHESIS**

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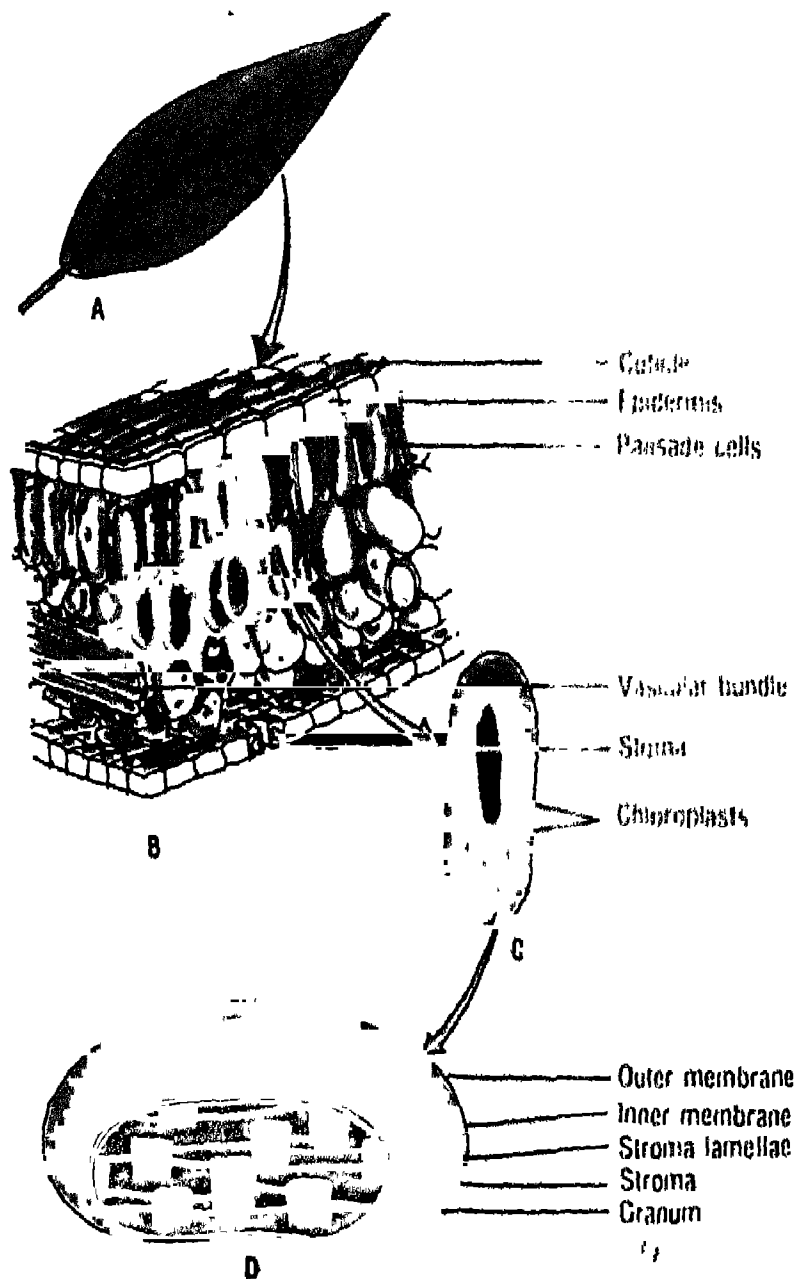
**PHOTOSYNTHESIS** literally means 'synthesis with the help of light'. Photosynthesis is the only process on earth by which solar energy is trapped by autotrophic organisms and converted into food for the rest of the organisms. About 170 million tonnes of dry matter are produced by this process annually, 90% of it in the oceans. No other chemical process on earth can match this output. Curiously, only 0.2% of the light energy incident on earth is utilised by photosynthetic organisms, yet this amount of trapped energy meets the food requirement of all other heterotrophs. In addition, people use plants for fodder, firewood, timber, fibres and many other purposes. Fossil fuels such as coal, petroleum and natural gas are also products of photosynthetic organisms which lived millions of years ago. Importantly, photosynthesis is the only natural process by which oxygen is liberated for use by other organisms.

**MAGNITUDE OF  
PHOTOSYNTHESIS**

The atmosphere contains only about 0.03% carbon dioxide by volume. But this small percentage represents about 2200 billion tonnes of it. This amount of carbon dioxide is sufficient to support photosynthesis for a few hundred years even if no further amount is added. The oceans of the earth contain over 50 times the amount of atmospheric carbon dioxide in the form of dissolved gas or carbonates. From these two sources about 70 billion tonnes of carbon are fixed annually by photosynthesis.

**Chloroplast — the Site of Photosynthesis**

All green parts of plants have chloroplasts, and leaves are the main site of photosynthesis (Fig 29.1). There may be over half a



**Fig. 29.1** The site of photosynthesis in plants.

A. Leaf is the major organ of photosynthesis in plants; B. Diagrammatic view of a section of leaf showing palisade cells C, which are rich in chloroplasts; D. Chloroplasts are enveloped by double membrane enclosing stroma, in which grana are present. The grana contain pigments such as chlorophyll.

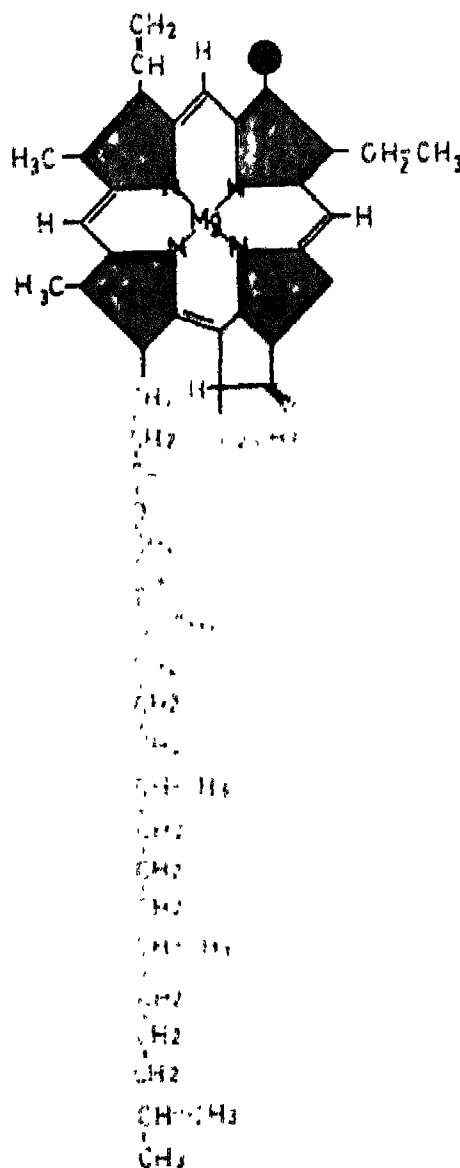
## PHOTOSYNTHESIS

million chloroplasts per square millimetres of leaf surface. Chloroplasts occur mainly in the mesophyll cells of leaves. These cells obtain carbon dioxide needed by them through the stomata. Water reaches them through the veins. Typical chloroplasts from higher plants are discoid or lens-shaped. You have learnt in chapter 9 that a chloroplast is an organelle with an outer envelope consisting of a double membrane. Stacks of thylakoids (grana) are located in the stroma and are connected by stroma lamellae. All the pigments are located in the thylakoid membranes. A pigment is a molecule that absorbs light of a specific wavelength in the visible region. The chloroplast pigments are fat soluble and are located in the lipid part of the membrane. Along with some enzymes they participate in the conversion of solar energy into ATP and NADPH. The stroma contains enzymes which are capable of utilising ATP and NADPH to produce carbohydrates.

Cyanobacteria and other photosynthetic bacteria do not have chloroplasts. However, their photosynthetic pigments are located on membranes. Their pigments are also different from those of other eucaryotes.

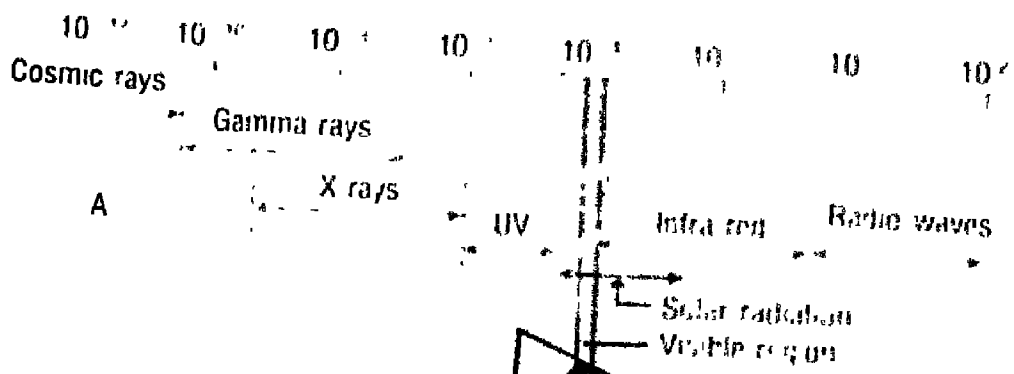
### The Chloroplast Pigments

Higher plants contain two predominant types of chlorophylls — chlorophyll *a* and chlorophyll *b*. The basic molecule consists of two parts (Fig 29.2): (i) A complex ring structure of alternating single and double bonds, the PORPHYRIN RING. It has magnesium at its centre. The porphyrin ring has several side groups which alter the properties of the pigment. Chlorophyll *a* and *b* differ in the nature of groups attached to position X. Chlorophyll *a* has a methyl group ( $-\text{CH}_3$ ) while chloro-



● Chlorophyll *a* ( $-\text{CH}_3$ )  
○ Chlorophyll *b* ( $-\text{CHO}$ )

**Fig. 29.2** Structure of chlorophyll *a* and *b*. The chlorophyll molecule consists of a magnesium core held in the centre of a porphyrin ring. Attached to the ring is phytyl, a long, lipid-soluble carbon chain. Chlorophyll *a* —  $\odot$  replaced by  $(\text{CH}_3)$  and chlorophyll *b* —  $\odot$  replaced by  $-\text{CHO}$  group.



B

Rate of photosynthesis

Action spectrum

C

% absorption

Absorption spectrum

Chlorophyll b

Chlorophyll a

400

500

600

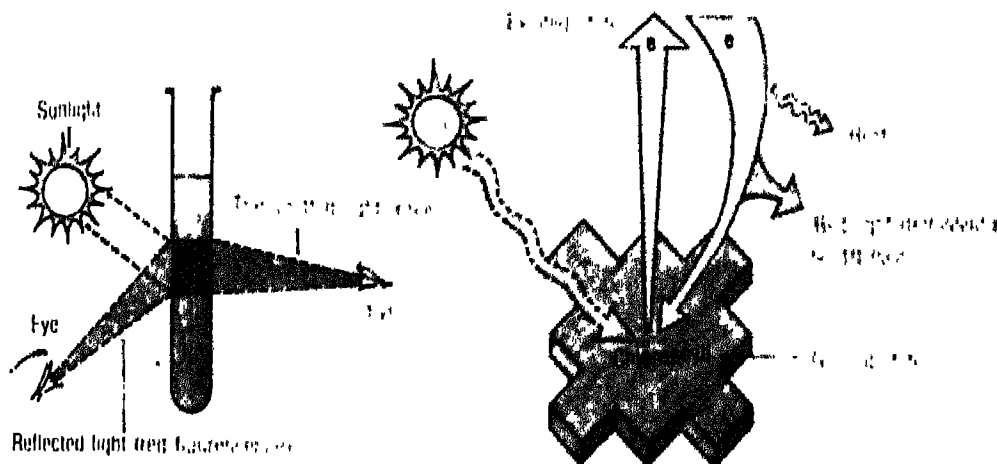
Wavelength (nm)

phyll *b* has an aldehyde group ( $-\text{CHO}$ ) and (ii) a lengthy hydrocarbon tail attached to the porphyrin group, called the **PHYTOL**.

Most plants contain two or three times more chlorophyll *a* than chlorophyll *b*.

Chlorophylls absorb light near both ends of the visible spectrum (Fig 29.3)— the blue and red light—and transmit or reflect green light. This is why chlorophyll appears green.

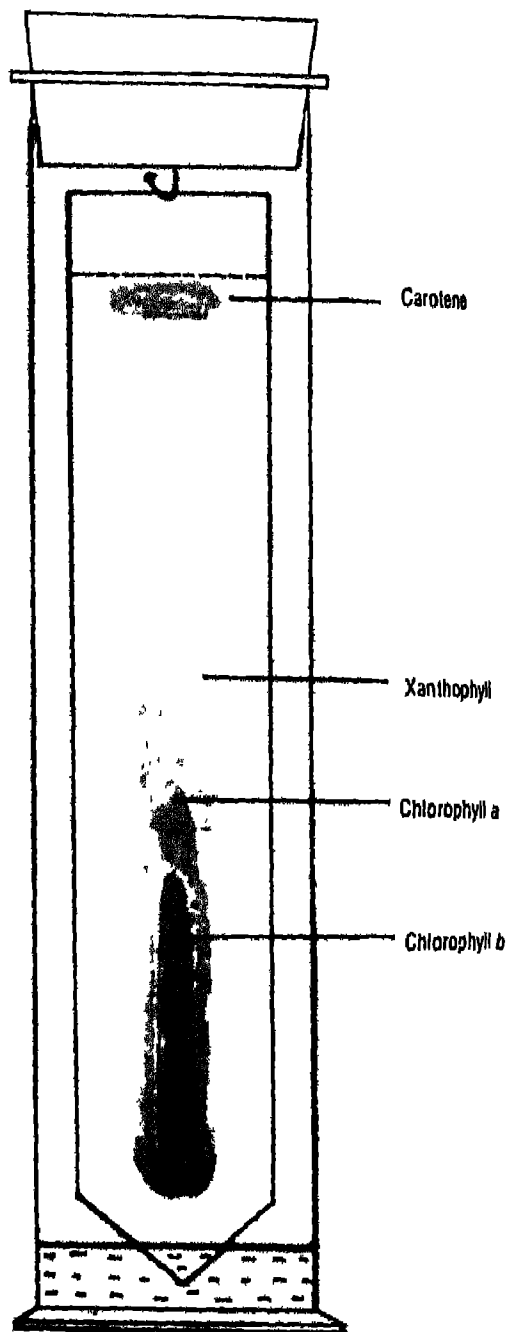
**Activity 1:** Grind some soft, green, non-mucilaginous leaves with acetone. Chlorophyll is soluble in this solvent. Filter out the coloured solution and observe the solution as shown in Fig. 29.4. When you observe the solution against transmitted light, that is, with the solution between you and the light source, it appears green. However, if you see the solution with the light behind you, that is, in reflected light, the solution appears red. The phenomenon is called **FLUORESCENCE**. The photons absorbed by the molecule lose some of their energy and are given out as red photons.



**Fig. 29.4** The phenomenon of fluorescence. Absorption of light or photon causes a transition of the chlorophyll molecule from its ground state to its excited state in extracted chlorophyll solution and it immediately drops back to the ground state within  $10^{-9}$  seconds.

All photosynthetic organisms have other pigments that absorb light between the red and blue region of the spectrum. In higher plants, these are mainly **carotenoids**. These are yellowish to orange pigments and absorb primarily in the violet to blue regions of the spectrum. One function of these pigments is to absorb light energy and transfer it to chlorophyll for use in photosynthesis. Their main function is to protect the chlorophyll molecule from photooxidation. You can extract the chloroplast pigments and separate them by paper chromatography.

**Activity 2:** In Activity 1, you had already extracted chlorophyll from leaves. Concentrate this solution by evaporation. Apply a tiny drop to one end (2 cm from edge) of a strip of chromatographic paper, and allow it to dry thoroughly. Hang the strip in a jar containing a mixture of petroleum ether (40-60°C) and acetone in the proportion 9:1, with its end dipping in the solvent (Fig. 29.5). Close the jar tightly and observe after one hour. The photosynthetic pigments would have separated into distinct green and yellow bands of chlorophylls and carotenoids respectively.



**Fig. 29.5** Paper chromatography of leaf pigments



### Absorption and Action Spectra

When the amount of light absorbed by a pigment is plotted as a function of wavelength, you will obtain what is termed the ABSORPTION SPECTRUM. The absorption spectrum of the photosynthetic pigments is shown in Fig 29.3. If the actual rate of photosynthesis in terms of oxygen evolution or carbon dioxide utilisation is measured as a function of wavelength, the ACTION SPECTRUM of photosynthesis (Fig 29.3) can be obtained. Chlorophylls

of the visible spectrum (Fig. 29.3). The main function of these pigments is to absorb light energy and then transfer it to chlorophyll for use in photosynthesis.

### Mechanism of Photosynthesis

The process of photosynthesis as we understand today is vastly different from what was thought some centuries ago. Ancient philosophers thought that plants derived their nutrition from the soil (also see Box). It was only in the 18th

#### NATURE OF LIGHT

Light is a form of energy and it appears to travel as a stream of tiny particles called PHOTONS. The energy contained in an individual photon is referred to as a quantum. Light is also described as having a wave nature, with different colours resulting from different wavelengths (Fig 29.3). Light is one part of electromagnetic radiation. Other parts are cosmic rays, gamma rays, X-rays, ultraviolet radiation, infra-red radiation and radio waves. These are listed in order of increasing wave length and decreasing energy per quantum. Most of us can see electromagnetic radiation with wavelengths ranging from 400 nm ( $4 \times 10^{-5}$  cm) to 700 nm and this part of the spectrum is called the visible light. Different colours related to wavelengths of the visible light are shown in Fig 29.3. Visible light in the electromagnetic spectrum lies between wavelengths of ultraviolet and infra-red.

absorb light near both ends of visible spectrum. However, all photosynthetic organisms possess some other pigments that absorb light between the blue and red region of the spectrum. In higher plants these pigments include carotenoids. These are yellowish to orange in colour and absorb primarily violet and blue light

century that the importance of air and light for nourishment of plants was recognised. Subsequently it was established that water and carbon dioxide are necessary for photosynthesis and that oxygen is evolved during the process. By the mid 19th century the process of photosynthesis was summarised as:



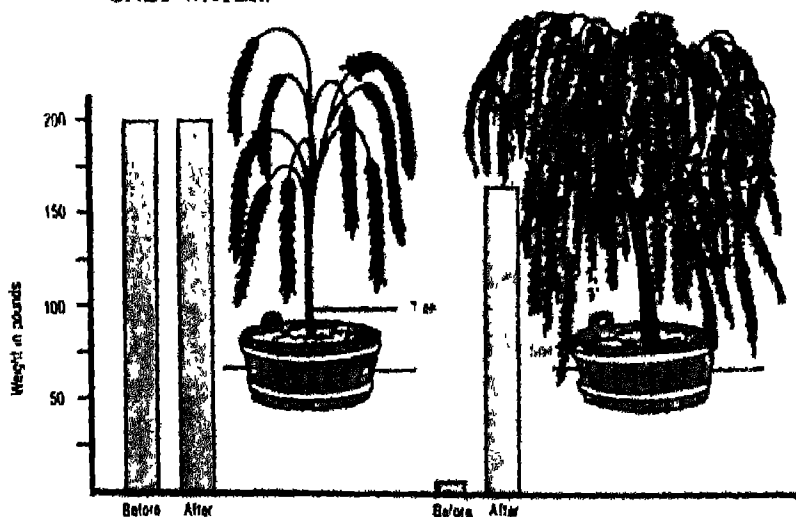
## LANDMARKS IN STUDIES ON PHOTOSYNTHESIS

It is very interesting to study how the concept of the process of photosynthesis evolved.

320 B.C. ARISTOTLE and THEOPHRASTUS: These great philosophers thought plants absorb all materials, inorganic and organic, directly from the soil.

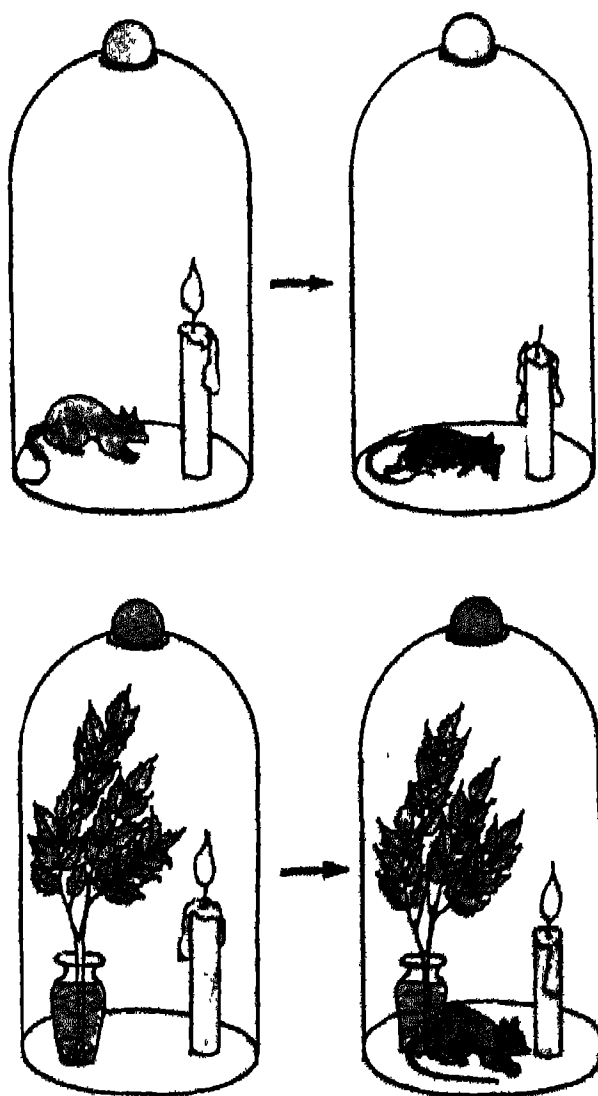
ANCIENT INDIANS : They believed that plants fed from their feet (the word *Padapa*, meaning that which drinks from the feet, is used in Sanskrit for a plant).

1648 VAN HELMONT : He grew a small willow twig, weighing 5 pounds, in a barrel containing pre-weighed, oven-dried soil. He watered it for five years with rain-water. The twig grew into a young tree which he carefully removed and weighed. It had gained 164 pounds and three ounces. He then re-dried the soil and weighed. It had only lost 2 ounces of the original weight. He, therefore, came to the conclusion that ALL VEGETATION IS ONLY WATER!



1727 STEPHEN HALES recognised the importance of air and light in the nourishment of plants.

1772 JOSEPH PRIESTLY carried out some very interesting experiments. He put a burning candle in a closed glass-container. He found that the air inside the jar had changed and would not allow another candle to burn or a mouse to live in it. Now he placed a twig of mint in an inverted glass jar in a vessel of water and found to his surprise several days later that "the air would neither extinguish a candle nor was it all inconvenient for the mouse which was put into it". He came to the conclusion that VEGETATION PURIFIES THE AIR WHICH HAD BEEN INJURED BY BURNING OF CANDLES. He called the air produced by burning



of candle as PHLOGISTON which is noxious for a mouse and said that plants convert it into DEPHLOGISTON.

1779 JAN INGEN-HOUZ discovered the role of light and green parts of the plants in purifying noxious air.

1783 LAVOISIER identified the purifying principle produced by green plants in sunlight as oxygen (dephlogiston) and the noxious air produced by the burning of candle as carbon dioxide (phlogiston).

1782 SENEBIER showed that as the concentration of  $\text{CO}_2$  is increased the rate of oxygen evolution also increases.

1845 VON MAYER recognised that green plants convert solar energy into the chemical energy of organic matter.



1845 LIEBIG pointed out that the organic matter was derived from  $\text{CO}_2$  and water was used in photosynthesis.

1862 SACHS reported that the product of photosynthesis was starch.

1888 ENGELMANN plotted the action spectrum of photosynthesis.

1905 BLACKMANN enunciated the law of limiting factors.

1920 WARBURG introduced the unicellular green alga *Chlorella* as a suitable material to study photosynthesis.

1932 EMERSON AND ARNOLD carried out the flashing light experiment and showed the existence light and dark reactions.

1937 HILL demonstrated photolysis of water by isolated chloroplasts in the presence of suitable electron acceptor.

1941 RUBEN AND KAMEN used  $\text{O}^{18}$  to show that in photosynthesis oxygen comes from water.

1954 ARNON, ALLEN AND WHATLEY used  $^{14}\text{CO}_2$  to show fixation of  $\text{CO}_2$  by isolated chloroplasts.

1954 CALVIN traced the path of carbon in photosynthesis and gave the C<sub>3</sub> cycle (now named after him). He was awarded the Nobel Prize in 1960.

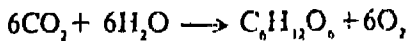
1965 HATCH AND SLACK reported the C<sub>4</sub> pathway for  $\text{CO}_2$  fixation in certain tropical grasses.

1985 HUBER, MICHEL AND DISSENHOFER crystallised the photosynthetic reaction centre of bacterium, *Rhodospirillum rubrum*. They analysed its structure by X-ray diffraction technique. The Nobel Prize in Chemistry for 1988 was awarded to them for this work.

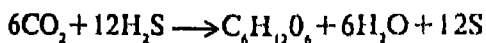
At the beginning of this century scientists observed that the rate of photosynthesis increased linearly at low light intensities and reached saturation at higher intensities. This led them to propose that photosynthesis not only involved reactions that occur in light but also others that are independent of light. This was later proved by other scientists by subjecting the unicellular alga *Chlorella* to either brief flashes of light or continued light at saturating intensities and observing oxygen evolution. The extent of photosynthesis

per unit of light energy received was higher when light and dark periods were alternated, thus verifying the hypothesis that the process of photosynthesis could be divided into LIGHT and DARK REACTIONS. This may be likened to a goods train with loaded wagons. The faster the wagons are unloaded on reaching destination, the quicker they become available for further haulage. The unloading of the wagons thus becomes the rate limiting step in the transport of goods. Another

that the oxygen evolved during photosynthesis came from water and not from carbon dioxide. The early model of photosynthesis presumed that carbon dioxide was split into carbon and oxygen and that carbon combined with water to form sugars. The oxygen evolved came from carbon dioxide.



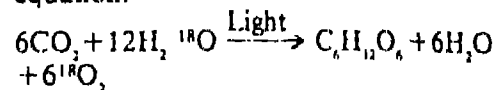
However, in 1931, a graduate student, Van Niel by name, observed that a certain type of photosynthetic bacteria fixed carbon dioxide in the presence of hydrogen sulphide. No oxygen was evolved. Instead globules of sulphur were formed as a waste product. He concluded that during bacterial photosynthesis carbon dioxide was not split, rather hydrogen sulphide was broken down, the hydrogen reduced carbon dioxide and sulphur was left behind.



This led Van Niel to hypothesise that

all photosynthetic organisms require a source of hydrogen. In plants this source was water, and the oxygen was evolved by the splitting of water.

Nearly 10 years later, this hypothesis could be proved by scientists using water, labelled with  $^{18}\text{O}$  (a stable isotope of oxygen), i.e.  $\text{H}_2^{18}\text{O}$ . The oxygen evolved contained  $^{18}\text{O}$ , thereby proving Van Niel's hypothesis that the oxygen evolved in photosynthesis comes from water. This led to the currently accepted general equation.



About the same time, it was also demonstrated that isolated chloroplasts in the absence of carbon dioxide would evolve oxygen when they are illuminated in the presence of a suitable electron acceptor such as ferricyanide. This is called HILL REACTION after its discoverer Robin Hill (see Box for details and Fig.29.6)

#### HILL REACTION

In 1937, R. HILL demonstrated that isolated chloroplasts evolved oxygen when they were illuminated in the presence of a suitable electron acceptor, such as ferricyanide. The ferricyanide is reduced to ferrocyanide by photolysis of water. This reaction, now referred to as the HILL REACTION, accounts for the use of water as a source of electrons for carbon dioxide fixation and the elimination of oxygen as a by-product during photosynthesis.

Hill reaction can be easily demonstrated in the classroom by using a coloured dye like dichlorophenol indophenol (DCPIP) which is blue in the oxidised state and colourless in the reduced state. When photolysis of water occurs by isolated chloroplasts the oxidised coloured dye (blue) will become colourless. This test indicates that photosynthesis is the light activated transfer of an electron from one substance to another involving oxidation ( $\text{H}_2\text{O} \longrightarrow \text{O}_2$ ) of one and reduction of the other (oxidised DCPIP to the reduced state).

DCPIP, dichlorophenol indophenol

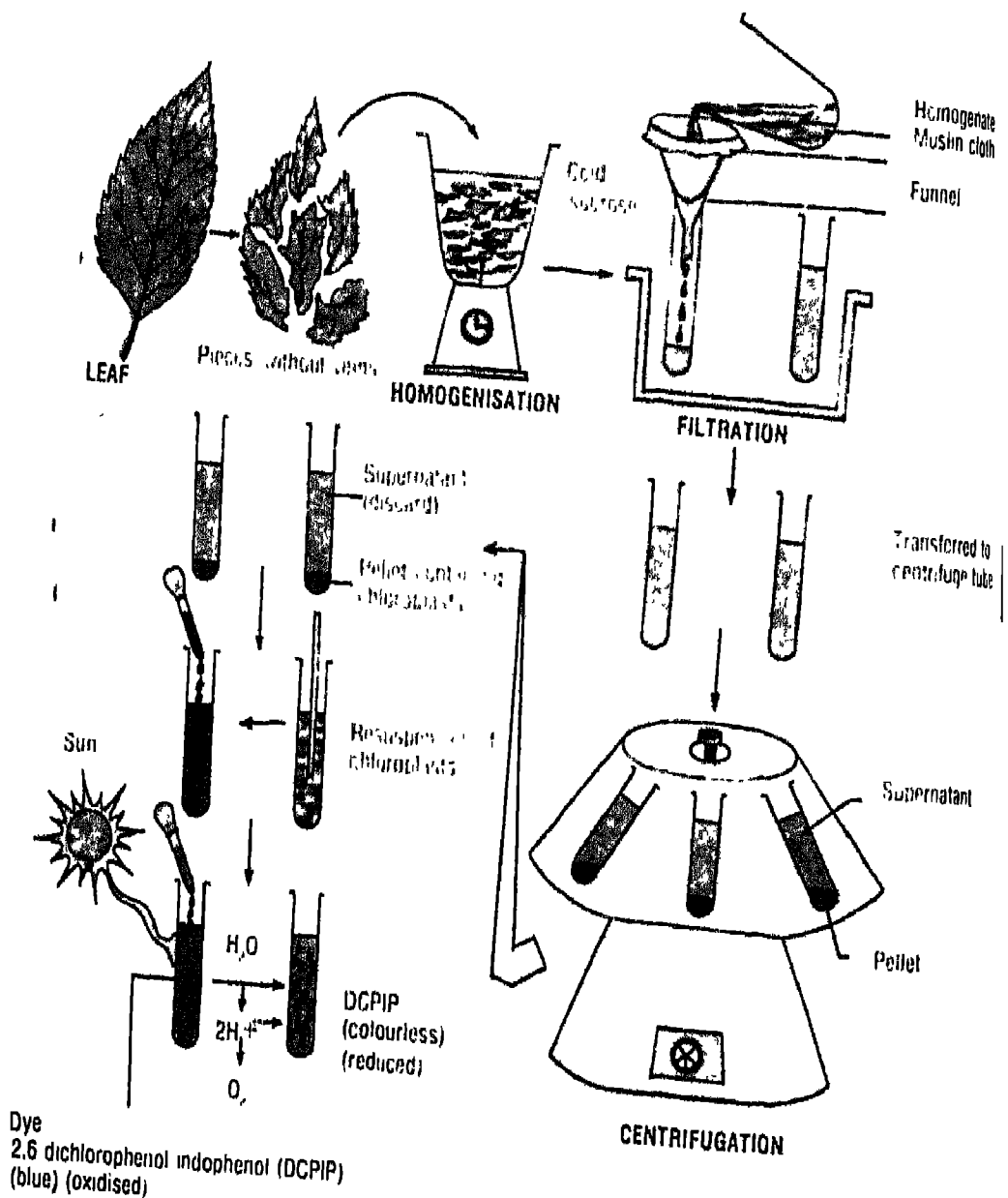


Fig. 29.6 Isolation of chloroplasts and demonstration of Hill reaction.

Presently it is established that photosynthesis consists of two steps: (i) **LIGHT REACTION** in which solar energy is trapped by chlorophyll and stored in the form of

chemical energy of ATP and as reducing power in NADPH. Oxygen is evolved in the light reaction by splitting of water. (ii) **DARK REACTION**, in which the reducing

capacity of NADPH and the energy of ATP are utilised in the conversion of carbon dioxide to carbohydrates. We shall now discuss the salient points of these two reactions.

### *Light Reaction*

The crucial question in the light reaction is: how to harvest the maximum amount of solar energy for conversion into chemical energy? You already know that the photosynthetic pigments are located in the thylakoid membranes. Situated in these membranes are clusters of chlorophyll and accessory pigments along with special types of chlorophyll molecule  $P_{680}$  and  $P_{700}$ . (The letter P stands for pigment and the figures for the wave length of light at which these molecules absorb).  $P_{680}$  and  $P_{700}$  molecules form the REACTION CENTRES or PHOTOCENTRES. The accessory pigments and other chlorophyll molecules harvest solar energy and pass it on to the reaction centres. The energy trapped by a single chlorophyll molecule is not enough to start the first chemical reactions that would occur in light. Chlorophyll and accessory pigments help capture light over a larger area and pass it on to the photocentres. Thus a photon absorbed anywhere in the harvesting zone of a  $P_{680}$  centre can pass its energy to the  $P_{680}$  molecule. The cluster of pigment molecules which transfer their energy to  $P_{680}$  absorb at or below the wavelength of 680 nm. Together with  $P_{680}$  they form the PHOTOSYSTEM II or PS II. Similarly,  $P_{700}$  forms PHOTOSYSTEM I or PS I along with pigment molecules which absorb at or below 700 nm (Fig 29.7). When the  $P_{680}$  acquires a sufficient quantum of energy, it emits an electron. This electron with high potential energy moves down an electron

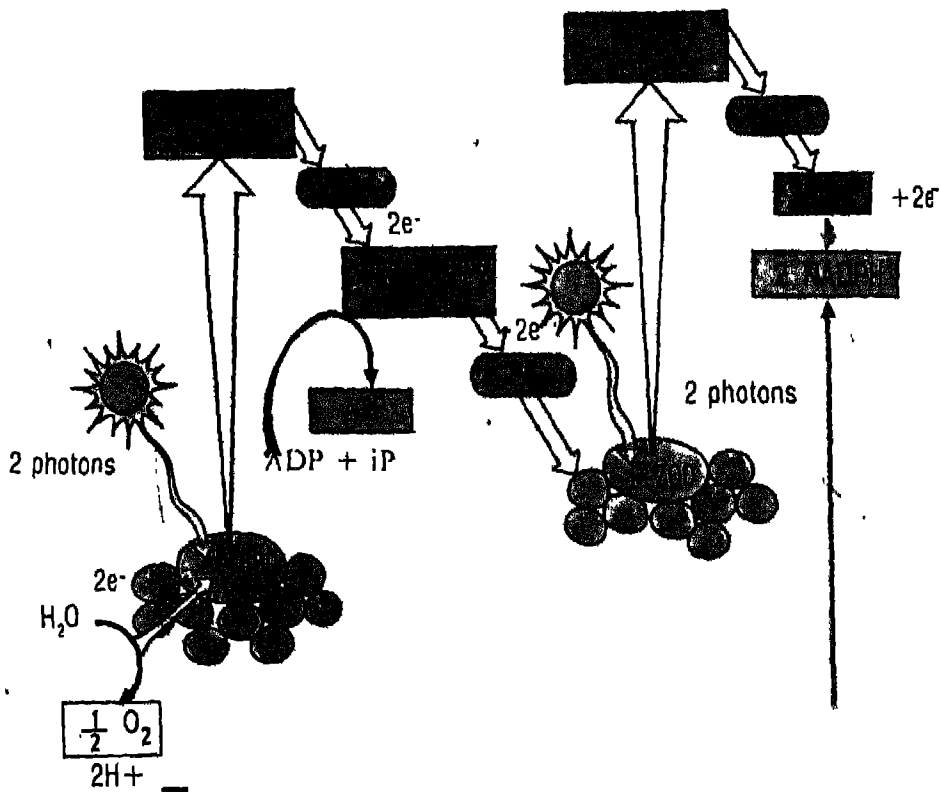
ATP is formed. The electron lost from  $P_{680}$  is ultimately accepted by  $P_{700}$  which transfers it to ferredoxin (an iron-containing protein). In turn ferredoxin transfers the electron to NADP to generate NADPH. You have already learnt in Chapter 10 how the electron transport chain operates in respiration.

In photosynthesis also, basically the same types of oxidation-reduction occur, but the members in the chain are different. The electron transport chains of photosynthesis involving the two photosystems are shown in Fig 29.7. The electron emitted by  $P_{680}$  is ultimately trapped by  $P_{700}$ . The oxidised  $P_{680}$  regains its electron by the photolysis of water into  $2H^+$ ,  $2e^-$  and oxygen. Oxygen is given out by photosynthesising plants. The protons ( $H^+$ ) accumulate inside the thylakoid membrane resulting in a PROTON GRADIENT. The energy released by the protons when they diffuse across the thylakoid membrane into the stroma (along the  $H^+$  concentration gradient) is used to produce ATP. This is similar to the production of ATP by the  $F_0F_1$  particles of the mitochondria. The electron emitted from the  $P_{700}$  is ultimately passed on to NADP (nicotinamide dinucleotide phosphate) along with the protons generated by the splitting of water. This results in the formation of NADPH. As synthesis of ATP occurs in light and the process is not cyclic (that is, it needs a constant supply of water molecules to be oxidised and NADP to be reduced), the process is called NON-CYCLIC PHOTOPHOSPHORYLATION.

The non-cyclic photophosphorylation is not the only mechanism for generating ATP during light reaction. A second electron transfer mechanism occurs, starting with  $P_{700}$ ; the ultimate acceptor of the

process is a cyclic one (Fig.29.8). It generates ATP and is, therefore, known as

CYCLIC PHOTOPHOSPHORYLATION. The ATP and NADPH generated in the light



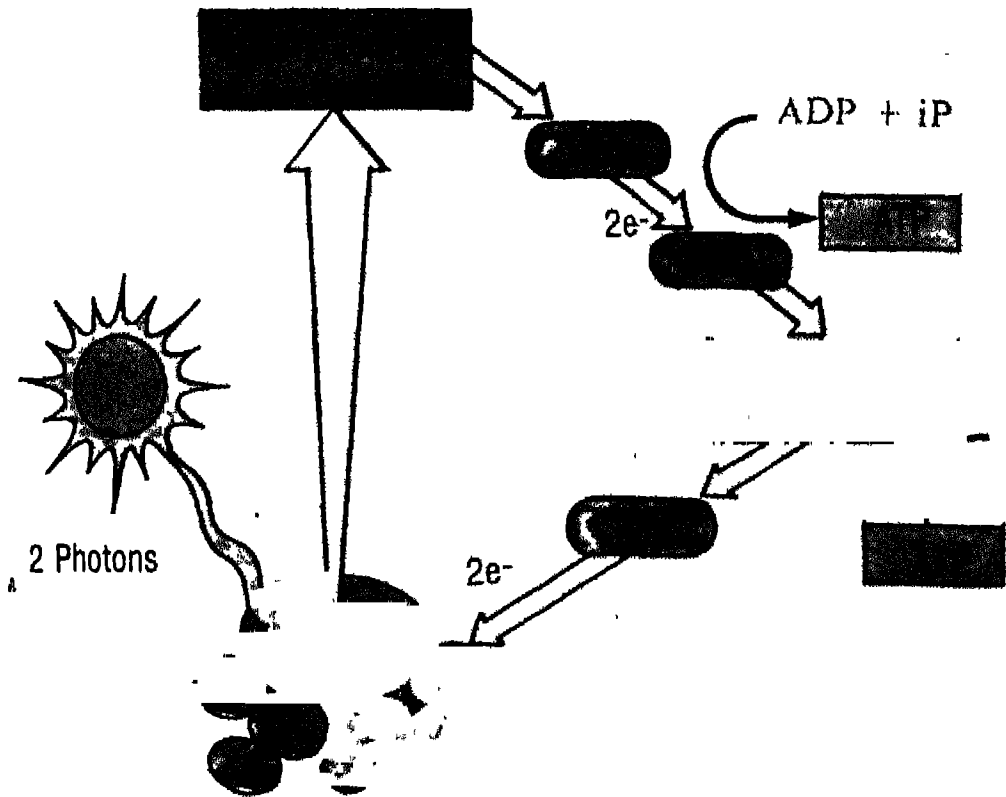
**Fig. 29.7** Non-cyclic photophosphorylation. When both photosystems are illuminated, there is a continuous current of electrons flowing from water to  $NADP^+$ . Electrons from  $P_{680}$  are replaced by electrons removed from water by splitting of water that evolves oxygen. The excited electron from  $P_{680}$  flows down an electron transport chain to  $P_{700}$  (PQ-plastoquinone, cytochrome complex, PC-plastocyanin) generating ATP. Illumination of PSI boosts electrons to high energy state which are passed to  $NADP^+$  reducing it to NADPH (protons from  $H_2O$ ). The net products of non-cyclic



reaction are used in the dark reaction to reduce carbon dioxide to carbohydrate, a process called CARBON FIXATION.

### Dark Reaction

Carbon fixation occurs in the stroma by a series of enzyme-catalysed steps. In this



**Fig. 29.8** Cyclic photophosphorylation. When the photons activate Photosystem I, a pair of electrons are raised to a higher energy level. They are captured by the primary acceptor, which passes them on to Ferredoxin (Fd), plastoquinone (PQ), cytochrome complex, plastocyanin (PC) and finally back to chlorophyll P700. The process is cyclic. At each step of electron transfer, the electrons lose potential energy. Their trip downhill is used by the transport chain to pump  $H^+$  across the thylakoid membrane. The proton gradient triggers ATP synthesis.

process, three molecules of carbon dioxide are attached to three molecules of ribulose 1, 5 biphosphate (RuBP), which is a 5-carbon sugar (pentose) with two phosphate groups attached to it. It was formerly termed ribulose diphosphate (RuDP). The discovery that a pentose phosphate was the acceptor of carbon dioxide was a major breakthrough in the study of the dark reactions of photosynthesis.

The whole dark reaction i.e. the path of carbon was worked out by an American scientist Melvin Calvin in 1954. The experimental strategy was to use radioactive  $^{14}\text{C}$  (which has a half-life of nearly 5200 years) to trace the fate of carbon dioxide. Radioactive  $^{14}\text{CO}_2$  was injected into an illuminated suspension of *Chlorella* cells that had been carrying out photosynthesis with normal carbon dioxide. The alga was killed after different intervals of time (in seconds) by dropping the suspension into hot methanol, which also stopped all enzymatic reactions. The radioactive compounds in the alga were separated by two dimensional paper chromatography. The paper chromatogram was then pressed against an X-ray film, which showed spots wherever the radioactive compounds were present. The compounds were identified later by comparing the rate of movement of the standard chemicals. This technique is called AUTORADIOGRAPHY. Calvin cycle can be divided into three distinct phases (Fig. 29.9): (i) carboxylation, (ii) glycolytic reversal and (iii) regeneration of RuBP. It takes six turns of the Calvin cycle to generate one molecule of hexose.

### *Phase 1---Carboxylation*

Three molecules of RuBP react with three molecules of carbon dioxide to produce short-lived six-carbon intermediates. This process is called CARBOXYLATION and involves the enzyme RuBP carboxylase or 'Rubisco'. The 6-carbon intermediates are immediately broken down into six molecules of 3-phosphoglyceric acid (PGA), a 3-carbon compound. Rubisco is a large protein molecule. It comprises 16% of the chloroplast protein and is the most abundant protein on earth.

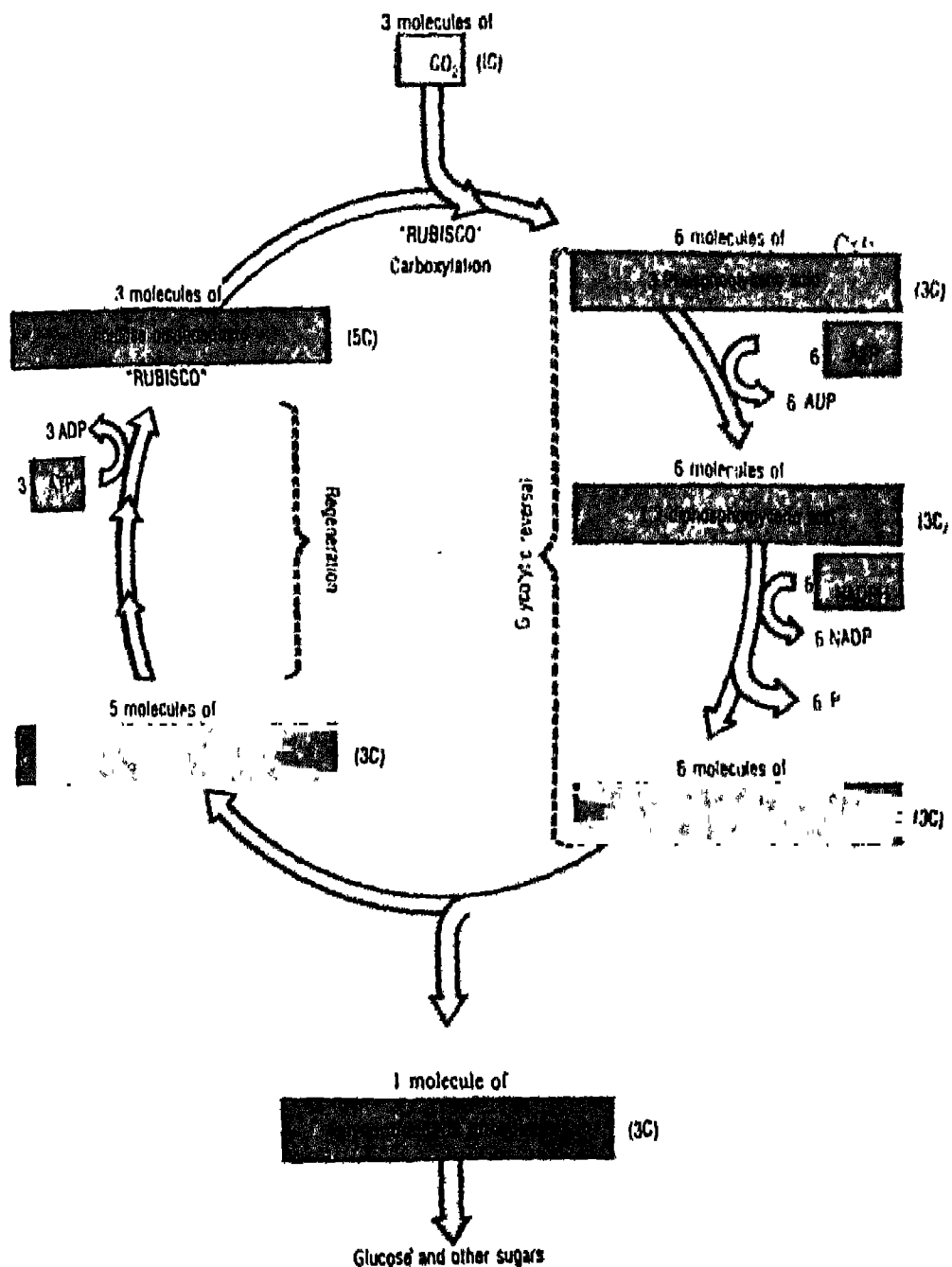
### *Phase 2---Glycolytic Reversal*

Six molecules of PGA form 1,3-diphosphoglyceric acid utilising six ATP molecules. These in turn get converted to glyceraldehyde phosphate utilising six NADPH supplied by the light reactions of photosynthesis. Indeed, these steps are essentially a reversal of glycolysis. However, the reducing power is obtained from NADPH, rather than NADP.

### *Phase 3---Regeneration of RuBP*

For the Calvin cycle to run continuously, there must be a regular supply of ATP and NADPH and also sufficient amount of RuBP which accepts carbon dioxide. A complex series of reactions utilising five molecules of phosphoglyceraldehyde and three molecules of ATP result in the regeneration of RuBP (see Box). As mentioned earlier, six turns of the cycle result in the production of one molecule of glucose. This glucose is used by the plant to form a large variety of organic compounds required for its structure and function. The dark reaction may be summed up as:





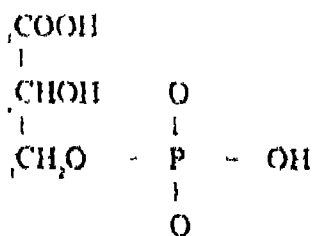
**Fig. 29.9** The Calvin cycle. For every three molecules of  $\text{CO}_2$  that enter the cycle, the net output is one molecule of glyceraldehyde phosphate, a three-carbon sugar. To fix the three  $\text{CO}_2$  molecules, the cycle spends nine molecules of ATP and six molecules of NADPH.

Thus the Calvin cycle regenerates ADP and NADP required for the light reaction. You would recall that the overall rate of photosynthesis is higher per unit of light energy received in flashes than continuously. The reason for this is that in flashing light ATP and NADP are regenerated for use in light reaction. However, in

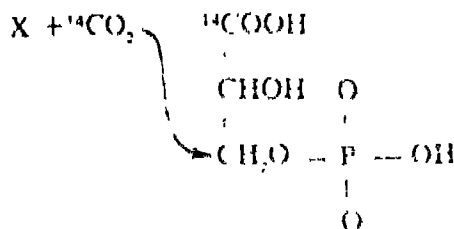
continuous light the dark reactions are slow and they do not regenerate sufficient ADP and NADP to utilise additional light energy. Thus the dark reaction of photosynthesis is the RATE LIMITING step, because it is the slower of the two reactions, and determines the rate of photosynthesis.

#### DEFECTIVE SEARCH FOR THE DARK REACTIONS

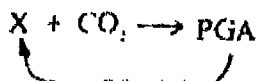
In the 1940s a big question in photosynthesis was : What is the reaction (s) through which atmospheric carbon dioxide becomes a part of carbohydrate? Melvin Calvin and his co-workers in California, USA attacked this problem. They asked a more specific question : What is the first reaction in which carbon dioxide is a reactant? It was important to detect the first product into which carbon atom of carbon dioxide is incorporated. Further, it was necessary to trace the path of this carbon through the various intermediate compounds in the dark reactions. This is a classical example of the application of the scientific method. Calvin and co-workers approached the following procedure : They fed  $^{14}\text{CO}_2$  to *Chlorella* only for 3 seconds so that  $^{14}\text{C}$  does not get enough time to move to another compound through the second reaction. They killed the cells immediately in boiling methanol. All the compounds in the algal extract were separated by chromatography, identified chemically and tested for radioactivity. Almost all the radioactivity was detected in one compound PGA, the first stable compound of photosynthesis. PGA is a compound with three carbon atoms :



These carbons are marked as C1, C2 and C3. Which of these carbon atoms belongs to carbon dioxide? The strategy to find this out is to separate out the C1, C2 and C3 from PGA and then examine which of these carbon atoms is radioactive. Calvin and co-workers observed that when the algal cells were fed with radioactive carbon dioxide for very short time (3 seconds), ONLY C1 WAS RADIOACTIVE. They concluded that C1 comes from carbon dioxide. Where do C2 and C3 come from? They must be coming from some other compound that reacts with carbon dioxide to produce PGA. If this unknown reactant is called X, then the reaction would be as follows :



What is this compound X? How many carbon atoms does it have? The answers were not known to anybody. But Calvin and co-workers observed further that when the algal cells were fed with  $^{14}\text{CO}_2$  for 60 seconds or longer, ALL THE THREE CARBONS OF PGA were radioactive. This was a very important clue to the investigation. Can you explain how C2 and C3 can become radioactive? Since C2 and C3 are coming from the unknown reactant X, this compound X must have become radioactive during the long term exposure of the algal cells to  $^{14}\text{CO}_2$ . Remember, PGA is the only compound that receives  $^{14}\text{C}$  from  $^{14}\text{CO}_2$ . Therefore, X must have received the radioactive carbons from PGA during the long-term exposure. How can that happen? The answer was a guess that came from another observation that after the long-term exposure, not only PGA, but many other compounds in the algal extract became radioactive. These compounds were mainly carbohydrates having four, five, six and seven carbon atoms. Therefore, it was suspected that there was a chain of reactions from PGA to all these carbohydrates and finally to X. In other words, it was suspected that the whole chain of reactions was operating in a cycle:



The search did not end there. Rather, the situation looked quite complex. Several questions had to be answered : One of the radioactive compounds detected in the chromatogram should be X. Which of them is X ? How many reactions are there in this cycle ? What is the sequence of these reactions ? Since these are biochemical reactions, these would be catalysed by enzymes. Can these enzymes be detected and characterised ? You can ask many other questions. And sure enough, all these questions were answered through intelligent hard work of many scientists for several years. Surprisingly, X turned out to be a 5-carbon compound, Ribulose 1,5 bisphosphate.

### Photorespiration

**RuBP carboxylase which is the main enzyme of photosynthesis also catalyses**

another reaction which interferes with the successful functioning of the Calvin cycle. In the presence of high concentration of

oxygen this enzyme acts as oxygenase and converts the RuBP to 3-carbon compound (PGA) and a 2-carbon compound (phosphoglycolate). This second reaction of RuBP carboxylase is important because the phosphoglycolate is converted quickly to glycolate. The peroxisomes present in the cell metabolise the glycolate into glycine, and glycine into serine and carbon dioxide without the production of ATP or NADH. The process is called **PHOTORESPIRATION**. This amount of carbon lost is not trivial. As much as half the photosynthetically fixed carbon dioxide may be lost by photorespiration. Photorespiration acts to undo the work of photosynthesis, as no energy-rich compound is produced during this process.

A characteristic of RuBP carboxylase is that with increase in temperature and oxygen concentration its affinity for carbon dioxide decreases and its affinity for oxygen increases. Thus, as temperature rises, more and more photosynthetically fixed carbon is lost by photorespiration. Overcoming the photorespiratory loss poses a challenge to plants growing in the tropics.

### *C<sub>3</sub> Pathway*

Many plants such as sugarcane and sorghum have adapted themselves to overcome the photorespiratory losses by an ingenious mechanism. The carbon dioxide is fixed in the mesophyll cells. The initial product being a 4-carbon compound, the process is called **C<sub>3</sub> pathway** of carbon dioxide fixation (Calvin's cycle is referred to as **C<sub>3</sub> pathway**). The carbon dioxide acceptor is a 3-carbon compound, phosphoenolpyruvate and it forms oxaloacetic acid, which is an intermediate in the citric acid cycle of respiration. Oxaloacetic acid is converted to another Krebs cycle intermediate malic acid,

which is then transported to cells surrounding the vascular bundle, the **BUNDLE SHEATH** cells (Fig. 29.10). Here malic acid (C<sub>4</sub>) is converted to pyruvic acid (C<sub>3</sub>) with the release of carbon dioxide. In some instances aspartate is formed instead of malate in the **C<sub>4</sub> pathway**. The concentration of carbon dioxide is thus increased in the bundle sheath cells. These cells contain Calvin cycle enzymes. Because of the high carbon dioxide concentration the RuBP carboxylase participates in Calvin cycle and not in photorespiration. The sugars formed in Calvin cycle are transported into the phloem.

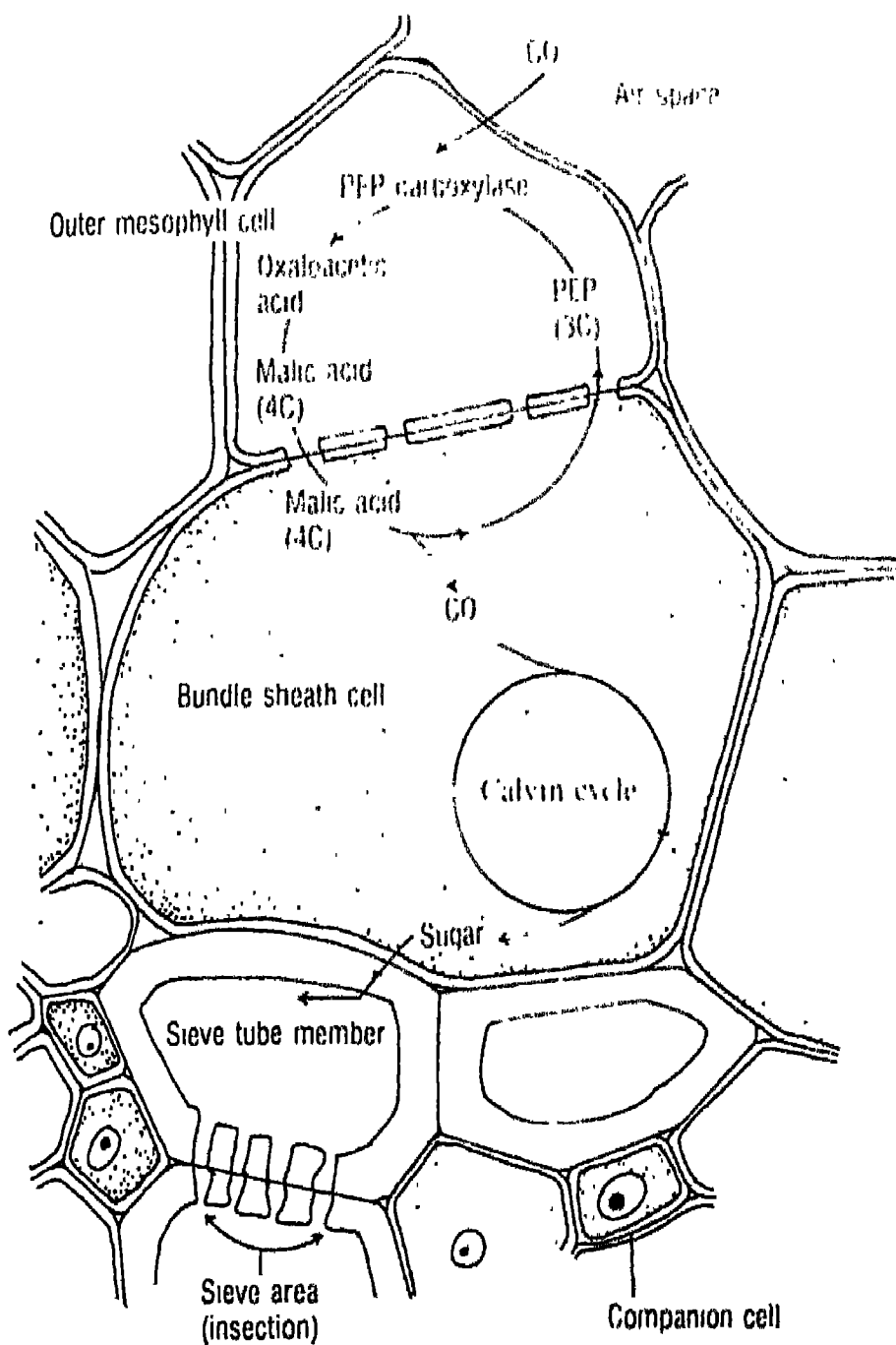
The pyruvic acid generated in the bundle sheath cells is transferred back to the mesophyll. It is converted to phosphoenolpyruvate by the expenditure of an ATP molecule. But because the conversion results in the formation AMP (and not ADP), the requirement to regenerate ATP from AMP is 2 ATP. This is how 12 additional ATPs are needed in the **C<sub>3</sub> pathway**. The **C<sub>3</sub> pathway** is thus more energy-expensive than the **C<sub>4</sub> pathway**. The **C<sub>3</sub> pathway** requires 18 ATP for the synthesis of one molecule of glucose, whereas the **C<sub>4</sub> pathway** requires 30 ATP. But realising that many tropical plants would otherwise lose more than half of the photosynthetic carbon in photorespiration, the **C<sub>3</sub> pathway** is of adaptive advantage.

### **Factors Influencing Photosynthesis**

A number of environmental factors are known to influence the rate of photosynthesis. These include intensity, quality and duration of light, availability of carbon dioxide and water, and temperature.

#### *Light Intensity and Quality*

In the total absence of light plants absorb



**Fig. 29.10** The C<sub>4</sub> pathway. Carbon dioxide is initially fixed in mesophyll cells by the enzyme PEP carboxylase. A four carbon compound, usually malic acid, conveys the CO<sub>2</sub> to bundle-sheath cells.

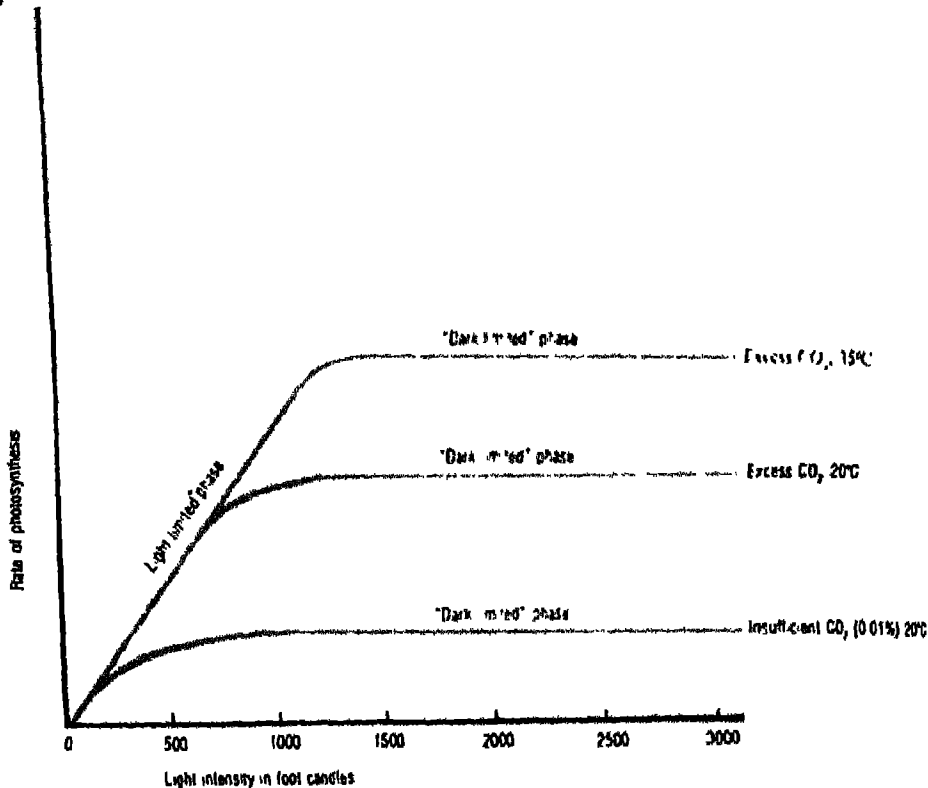


Fig. 29.11 Blackmann's Law of limiting factors. Rate of photosynthesis as a function of light intensity,  $\text{CO}_2$  concentration, and temperature. At low light intensities, light is the limiting factor. At higher light intensities, temperature and  $\text{CO}_2$  concentration are the limiting factors.

oxygen and release carbon dioxide (respiration). When light of sufficient intensity is available plants begin to perform photosynthesis; they absorb carbon dioxide and release oxygen.

As the light intensity is increased the rate of photosynthesis increases proportionately until some other factor such as carbon dioxide becomes limiting. Ultimately the plant becomes **LIGHT SATURATED** indicating that light is no longer the limiting factor in determining the rate of photosynthesis. If now the concentration of carbon dioxide is increased, the rate of photosynthesis increases until light becomes a limiting factor (Fig. 29.11).

The quality of light also influences pho-

tosynthetic rate. For example, when light passes through a forest canopy there is preferential absorption of blue and red regions of visible light (which are photosynthetically most effective) by the foliage. As a result the rate of photosynthesis in plants growing under the canopy markedly decreases.

#### *Availability of Carbon Dioxide*

In land plants the bulk of carbon dioxide enters the leaf through stomata. When the stomata are closed, the availability of carbon dioxide for photosynthesis decreases and ultimately the photosynthetic rate is reduced to zero. In submerged water plants, carbon dioxide directly enters through the epidermis and reaches the



photosynthetic cells in the form of bicarbonates or carbonates.

Carbon dioxide is usually the limiting factor in photosynthesis under field conditions, particularly on clear summer days when plants are provided with adequate water.

#### *Availability of Water*

Under field conditions, water may be a limiting factor for photosynthesis, not only during prolonged drought periods but also every afternoon, particularly during hot weather. Although water supplies electrons in the photo-chemical phase, the primary effect of reduced water availability for photosynthesis is through the closure of stomata. When stomata are completely closed, photosynthesis may cease. In addition, the decrease in the availability of water leads to dehydration of protoplasm which ultimately affects the enzymes involved in photosynthesis.

#### *Temperature*

Temperature is a limiting factor under field conditions particularly on cool days. The influence of temperature on photosynthesis depends on both light intensity and availability of carbon dioxide. An increase in temperature above 30°C results in a decrease in the rate of photosynthesis. Changes in temperature do not affect the light reactions of photosynthesis but profoundly influence the rate of enzyme-controlled dark reactions. However, the effect of temperature on the rate of photosynthesis varies from plant to plant. For example, C<sub>4</sub> plants show higher temperature optimum for photosynthesis than the C<sub>3</sub> plants.

#### *Internal Factors*

Besides the environmental factors, certain internal features of the plant like the age of leaf, its anatomy and chlorophyll content affect the photosynthetic process. As the

leaf develops, the rate of its photosynthesis increases gradually reaching a maximum at its fully expanded stage. Later, photosynthesis gradually decreases with the age of the leaf.

The rate of photosynthesis is partly influenced by the number and degree of opening of stomata, extent of venation and the volume of intercellular spaces.

Under natural conditions, chlorophyll content of leaves is not generally a limiting factor in photosynthesis. For example, the sun plants contain less chlorophyll in their leaves than those of shade plants but still exhibit higher rates of photosynthesis over shade plants.

#### *Translocation of Photosynthates*

The carbohydrates manufactured in the leaves of higher plants are distributed to roots and storage organs (tubers, bulbs, roots, fruits, etc.) along the phloem. This long distance movement of organic compounds is called TRANSLOCATION. Sucrose is the principal form in which the carbohydrates are translocated. Sieve elements which are living (chiefly sieve tube members in seed plants) are the channels of transport. Metabolic energy is used in the process and rates up to 100 cm/hr have been recorded.

The mechanism by which carbohydrates and other organic molecules are translocated within vascular plants is not yet fully understood. Several theories have been proposed to explain translocation. Among them the mass flow hypothesis is the most widely accepted. In brief, this theory envisages a pressure gradient between the source (leaves) and the sink (storage organ). The difference in hydrostatic pressure between these is the driving force which moves the sugar solution.

## SUMMARY

Photosynthesis is the process by which green plants trap solar energy and convert it into chemical energy of carbohydrates. Photosynthesis is the only source of energy for all organisms. Additionally, this is the only natural process by which oxygen is liberated into the atmosphere. Photosynthesis involves two distinct phases : photochemical phase (light reactions) and biosynthetic phase (dark reactions). The first step in photosynthesis is the absorption of light by chlorophyll molecules, which are organised into photosynthetic units in the thylakoid membrane of the chloroplasts. The excitation energy is transferred from one chlorophyll molecule to another until it is trapped by a reaction centre. The critical event at the reaction centre is the light-activated transfer of an electron to an acceptor molecule resulting in the production of reducing power. Photosynthesis in green plants requires the interaction of two light reactions. Photosystem I generates strong reductant NADPH. Photosystem II produces a strong oxidant that forms oxygen from water.

Electrons flow through the electron-transport chain from photosystem II to I, which in turn leads to the synthesis from water to NADP with concomitant generation of ATP, NADPH and oxygen. This process is termed as non-cyclic photophosphorylation. Alternatively, ATP can be generated without formation of NADPH by a process called cyclic photophosphorylation involving absorption of light by only photosystem I. The mechanism of formation of ATP in the chloroplast is similar to that occurring in the mitochondria.

In the dark reaction, also called CALVIN CYCLE, the carbon dioxide is fixed and reduced to carbohydrate in the stroma part of the chloroplast, using ATP and NADPH generated through light reaction (the light reaction goes on in the lamellae of chloroplast). The dark reaction primarily consists of three major steps: (i) carboxylation, (ii) glycolytic reversal and reduction and (iii) regeneration. Carboxylation involves addition of carbon dioxide to ribulose 1,5 bisphosphate (RuBP) to form two molecules of phosphoglyceric acid in the presence of the enzyme ribulose bisphosphate carboxylase (Rubisco). In the glycolytic reversal step, PGA is reduced to phosphoglyceraldehyde, utilising ATP and NADPH generated in the light reactions. The two molecules of PGA combine to form fructose 6 phosphate. RuBP is regenerated through a complex series of reactions. Six turns of the Calvin cycle yield one molecules of glucose. Under high temperature and oxygen concentration Rubisco catalyses photorespiration rather than Calvin cycle. Photorespiration causes a high loss of fixed carbon without producing energy-rich compounds.

Plants such as sugarcane and sorghum fix carbon dioxide into phosphoenolpyruvate ( $C_3$ - compound) to produce  $C_4$  acid (usually malic acid). Such plants are called  $C_4$  plants. The  $C_4$  acids later release  $CO_2$  for producing sugars through Calvin cycle in the bundle sheath cells. By this pathway the  $C_4$  plants partially overcome the disadvantages of photorespiration.

The external factors affecting the rate of photosynthesis are intensity and quality of light, carbon dioxide, water and temperature. The age of leaf, chlorophyll content and the histology of the leaf are the major internal factors which control the rate of

Sugars manufactured in the leaf are translocated to storage organs through the phloem in the form of sucrose. Translocation is a metabolic process and occurs due to differences in hydrostatic pressure between the source (leaf) and sink (storage organ).

## QUESTIONS

1. Tick (✓) the correct answer in the following :
  - (a) A cell that lacks chloroplast does not
    - (i) evolve carbon dioxide
    - (ii) liberate oxygen
    - (iii) require water
    - (iv) utilise carbohydrates
  - (b) Energy is transferred from the light reaction step to the dark reaction step by
    - (i) chlorophyll
    - (ii) ADP
    - (iii) ATP
    - (iv) RuBP
2. Describe the light-dependent steps of photosynthesis. How are they linked to the dark reactions ?
3. Distinguish between :
  - (a) Respiration and photorespiration
  - (b) Absorption spectrum and action spectrum
  - (c) Cyclic photophosphorylation and non-cyclic photophosphorylation
4. What are the steps that are common to  $C_3$  and  $C_4$  photosynthesis ?
5. Are the enzymes that catalyse the dark reactions of carbon fixation located inside the thylakoids or outside the thylakoids ?
6. Calvin cycle consists of three phases. What are they ? Explain the significance of each of them.
7. Why are plants that consume more than the usual 18 ATP to produce 1 molecule of glucose favoured in tropical regions ?
8. What is the advantage of having more than one pigment molecule in a photocentre ?
9. Why does chlorophyll appear green in reflected light and red in transmitted light ? Explain the significance of these phenomena in terms of photosynthesis.
10. Explain why photosynthesis is considered the most important process in the biosphere.



## REPRODUCTION IN FLOWERING PLANTS

ALL living organisms reproduce. Reproduction is the means of perpetuation of species. In plants a new individual may be produced from a single parent or from two parents, depending on the mode of reproduction.

### MODES OF REPRODUCTION

Plants exhibit several modes of reproduction, which may be broadly grouped into two types : **ASEXUAL REPRODUCTION** and **SEXUAL REPRODUCTION**. In the former, new individuals are produced without the fusion of gametes. In sexual reproduction, fusion of gametes is required to form a new plant.

#### Asexual Reproduction

In Unit Three, you have read about various types of asexual reproduction in microorganisms. As only mitotic divisions are involved in asexual reproduction, the newly formed individuals are genetically identical to the parent plant.

method of reproduction as you have studied in Unit Three.

Regeneration of new plants from portions of vegetative organs is very common and is called vegetative propagation. In this chapter you will study some aspects of vegetative propagation in flowering plants. Stems, roots and leaves are variously modified to aid natural vegetative propagation. Humans have developed several techniques for the artificial vegetative propagation of economic plants.

#### *Natural Vegetative Propagation*

(i) *Vegetative Propagation by Stems*: You studied about the various types of modification of stem in Chapter 26. Runners, rhizomes, bulbs, corms and tubers serve as means of propagation.

(ii) *Vegetative Propagation by Roots*: The intact roots of many woody plants (*Murraya* spp., *Albizia lebbek*, *Dalbergia sissoo*) put out shoots and produce new plants. Tuberous roots such as sweet

yams also provide a means of vegetative propagation by producing adventitious buds that develop into new plants.

(iii) *Vegetative Propagation by Leaves*: Leaves are not a common means of vegetative propagation in nature. However, in some species of *Bryophyllum* (*B. daigremontianum*), plantlets develop

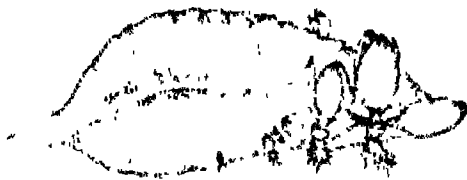


Fig. 30.1 Buds present in the notches along the margin of a *Kalanchoe* leaf form plantlets.

along the margins of intact leaves (Fig. 30.1). These plantlets become detached and develop into independent plants. In other species of *Bryophyllum* and *Kalanchoe* the leaves must be detached or injured before plantlets arise. You may like to examine the conditions under which propagation occurs from the leaves of *Bryophyllum* in your garden. Other horticultural plants propagated by leaf cuttings are *Begonia*, *Streptocarpus* and *Saintpaulia*.

#### *Vegetative Propagation from Reproductive Organs*

Although flowers are primarily associated with sexual reproduction, in the century plant (*Agave* sp.) flower buds develop into bulbils which drop to the ground and

#### *Artificial Vegetative Propagation*

Horticulturists use the various means of natural vegetative propagation explained above for commercial purposes. The chief advantage of vegetative propagation is the perpetuation of the desirable features of a selected plant. A population of genetically identical plants derived from an individual is called a **CLONE**. You are familiar with the knowledge that potatoes are propagated by whole tubers or their pieces; ginger and banana by the division of rhizome; onion by bulbs and mint by runners. In addition to these, several artificial methods of vegetative propagation have been practised. Some of these are **CUTTING**, **LAYERING** and **GRAFTING**.

**Cuttings** : The division of any plant organ (stem, root or leaf) used for propagation is referred to as a cutting. Stem cuttings are most commonly used for this purpose. Factors such as the optimal length and diameter of the cutting, age of the parent plant and season have to be taken into consideration for each species. Sugarcane, grapes, cocoa, rose, bougainvillea and carnations are some of the plants propagated by stem cuttings. Stem cuttings of some plants do not produce roots readily and have to be treated with hormones.

**Layering** : In this technique roots are induced on a stem before it is detached from the parent plant for propagation. There are several methods of layering. In **MOUND LAYERING**, the lower branch of a plant (jasmine and strawberry) is bent down close to the ground and covered with moist earth in such a way that its growing tip remains above the soil surface. After a few days the covered portion



Fig 30.2 Bulbils of *Agave* sp (Photo: H.Y Mohan Ram)

grown as an independent plant. In **AIR LAYERING**, the stem is girdled (a ring of bark tissue is removed) or slit at an upward angle, and covered with moist moss or cotton and wrapped with a polythene sheet. After the injured part produces roots, the branch is cut and planted separately.

**Grafting** : The art of joining parts of plants such that they grow as one plant is called **GRAFTING**. This is a feature unique to plants (especially dicotyledonous plants) and was described by ancient gardeners long before scientific horticulture became established. The part of the graft which gives rise to the upper portion is termed **SCION** and the part that becomes the supporting portion (usually the root) is

called the **STOCK** (Fig.30.3). Such composite plants are usually produced for economic benefits. The scion is obtained from a plant with superior characters while the root stock is derived from a plant resistant to diseases and pests and efficient in absorption of water and minerals. High quality roses are usually grafted on wild rose root stocks. Grafting is generally done between related varieties and species. There are various methods of grafting, including a technique where only a single bud instead of a scion is employed (budding). Grafting is routinely used for the propagation of rubber, apple, pear, citrus, mango and guava.

#### *Propagation by Plant Tissue Culture*

In Unit One you learnt about the tech-



**Fig. 30.3** Grafting

A. The lower part of the stem of scion is cut into a wedge; B. The shoot of the plant to be used as a stock is cut off. The stem is slit vertically. The scion is inserted into the stock and is tied with a tape (C). The graft union occurs within a short time.

nique of tissue culture. Using shoot tips or other suitable plant parts, it is possible to obtain a large number of plantlets. Tissue culture technique has been commercially used for the micropropagation of orchids, carnation, gladiolus, chrysanthemum and other ornamental plants. Usually the tissues in the shoot apical meristem are virus-free and therefore this method is also useful for producing healthy plants, especially in potato, tapioca and sugarcane. In addition, this technique enables production of an unlimited number of plants within a relatively short time. You will learn more about tissue culture in the next part of this textbook.

#### *Importance of Vegetative Propagation*

The most obvious benefit of vegetative propagation is that it makes possible the propagation of plants such as banana, seedless grapes and oranges, rose, and jasmine that have lost their capacity to produce seeds through sexual reproduction. Other plants such as Bermuda grass or doob grass (*Cynodon dactylon*), which produce only a small quantity of seed, are mostly propagated vegetatively. Vegetative propagation is a more rapid, easier and a less expensive method of multiplying plants which have either poor seed viability or prolonged seed dormancy. The greatest advantage of vegetative propagation is that all plants produced will have the same characters and hereditary potential as the parent plant. Grafting permits the physical and physiological joining of separate individuals to the best economic advantage.

#### **Sexual Reproduction in Flowering Plants (Angiosperms)**

In Chapter 17 you studied briefly about sexual reproduction in algae, bryophytes,



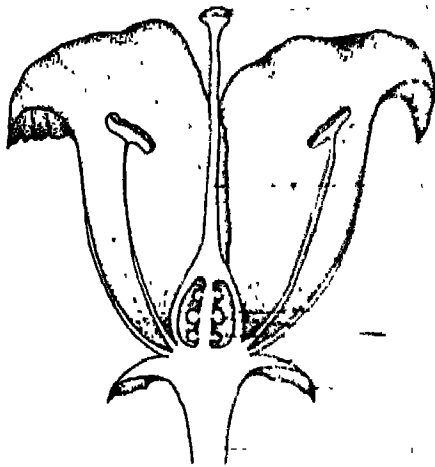


Fig. 30.4 A vertical section of a flower showing the position and arrangement of various floral organs

pteridophytes and gymnosperms. You also learnt that in angiosperms seeds are enclosed in an ovary. You will now learn more details about sexual reproduction in angiosperms.

### *Structure of the Flower*

The flower and its parts are concerned with sexual reproduction in angiosperms. Morphologically, the flower is considered as a shoot bearing nodes and modified 'floral leaves'. Unlike the condition in a vegetative shoot, the internodes in the flower are condensed and the number of appendages arising at a node are more numerous. Flowers exhibit wide variation in size, shape, colour and arrangement of floral parts. However, all flowers have the same basic plan (Fig. 30.4)

The stalk of the flower is called PEDICEL. The tip of the pedicel continues as an enlarged axis—the RECEPTACLE or THALAMUS. All other floral appendages (organs) are attached to the receptacle.

SEPALs are green, leaf-like structures that arise at the base of a flower and form the outermost circle of appendages. Collectively the sepals are referred to as CALYX. The sepals mainly protect the flower before it opens. The whorl of appendages that arise inner to the sepals are petals, collectively called COROLLA. Petals are generally brightly coloured and sometimes fragrant to attract insects. The third group of appendages consists of stamens, collectively called the ANDROECIUM. Each stamen may be regarded as a highly modified leaf (microsporophyll). It consists of a slender stalk, the FILAMENT and a bilobed structure at its tip, the ANTHER. The anther usually contains four microsporangia which produce a large number of pollen grains. The stamens are the male reproductive organs of the flower. The centre of the flower contains the female reproductive whorl called the GYNOECIUM OR PISTIL. It is composed of one or more CARPELS. Each carpel consists of three distinct parts—STIGMA, STYLE and OVARY. Ovary is the swollen basal part of the carpel which bears one or several ovules. The ovary extends at the tip into a slender style, which in turn terminates into a lobed head called the stigma. A flower may have only one carpel or several carpels. The carpels may be free or fused. The ovary may be one chambered or many-chambered. Inside the ovary the ovules develop from a special tissue called the PLACENTA. The manner in which the placentae are distributed in the ovary is known as PLACENTATION

The number of floral organs, their condition (free or united) and arrangement on the thalamus are characters used in identification and classification of plants. When the ovary is situated on the torus above all the other floral parts the

Fig. 30.5 Vertical section of a perigynous flower

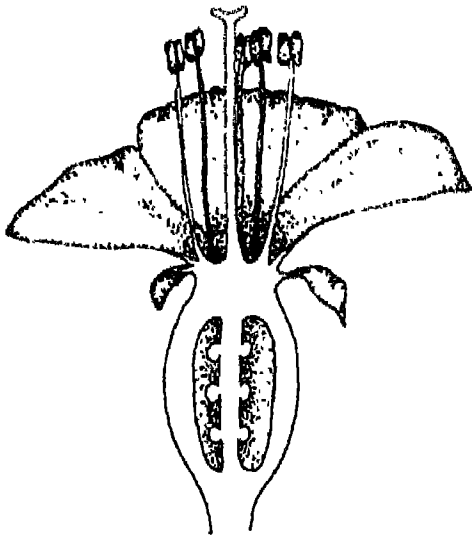
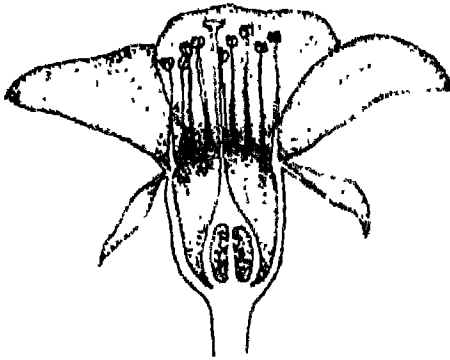


Fig. 30.6 Vertical section of an epigynous flower

flower is said to be HYPOGYNOUS (mustard, tomato) (Fig. 30.4). In such a flower the ovary is said to be superior. In some flowers such as the rose, the thalamus forms a cup-shaped structure around the ovary and bears sepals, petals and stamens. Flowers of this type are called

PERIGYNOUS (Fig. 30.5). When the thalamus is not only cup-shaped but is fused with the ovary such that the other floral parts arise on the top of the ovary, the flower is said to be EPIGYNOUS. The ovary in this case is inferior (Fig 30.6) (cucumber, apple).

Flowers that contain both stamen and pistil are termed HERMAPHRODITE or INTERSEXUAL. Flowers that bear organs of only one sex (staminate or pistillate) are called UNISexual. The unisexual flowers may be separated in time and space. Plants (such as cucurbits, maize and castor bean) that bear flowers of both sexes are called MONOECHOUS. Very rarely individuals of a species produce exclusively staminate or pistillate flowers. Such plants are called DIOECIOUS and can be compared to mammals in their sex expression. Date palm, mulberry and Coccinia grandis are good examples of dioecious plants. In mango and cashew plants, neuter, male and intersexual flowers occur together.

#### Inflorescence

Flowers do not always occur singly. They are often borne in clusters. An axis bearing a cluster of flowers is known as inflorescence. It may be terminal or axillary. When the flowers in an inflorescence are arranged acropetally (the lower or outer flowers being older) on the main axis which has unlimited growth, it is called a RACEMOSE inflorescence. When the main axis is always limited, ends in a flower and the subsequent growth of the inflorescence is carried out by axillary branches, the inflorescence is called CYMOSE. In a cymose inflorescence the terminal flower is the oldest. Racemose inflorescence is subdivided into seven types and cymose inflorescence into three types. There are

Table 30.1

MAIN TYPES OF INFLORESCENCE  
RACEMOSE

	<i>Spike</i>	<i>Catkin</i>	<i>Spadix</i>	<i>Corymb</i>	<i>Umbel</i>	<i>Head or Capitulum</i>
<i>sme</i> elongated bearing ed flowers stard)	Same as raceme but flowers have no stalks ( <i>Achyranthes</i> )	Spike with unisexual flowers ( <i>Mulberry</i> )	Spike with fleshy axis enclosed by one or more large bracts (Banana, <i>Colocasia</i> )	The axis is short and the lower flowers have longer stalks than the upper ones. Thus all flowers come to the same level ( <i>Candytuft</i> )	The axis is short and bears a cluster of flowers with stalks of equal length arising from a common point. The umbel is generally branched ( <i>Carrot</i> , <i>coriander</i> )	The main axis is a flattened, more or less convex structure on which stalkless flowers (called florets) are arranged in a centropetal order. The inflorescence is surrounded by prominent bracts ( <i>Sunflower</i> , <i>margold</i> )

## CYMOSE

<i>rhachial cyme</i> main axis terminates in a flower and lateral branch axis develops from its which also ends in a flower. This pattern appears ( <i>Begonia</i> , <i>Cotton</i> ).	<i>Dichasial cyme</i> Two lateral branches develop on either side of the terminal flower of the main axis. the lateral branches also end in a flower and may again branch similarly ( <i>Jasmine</i> , <i>Dianthus</i> ).	<i>Polychasial cyme</i> More than two lateral branches arise from the base of the terminal flower ( <i>Calotropis</i> )
<i>stithodium</i> main axis forms a cup-shaped receptacle a small opening at the top. Flowers are ed within the cup in cymose groups	<i>Cyathium</i> In this inflorescence the involucre forms a cup. Single female flower (without perianth) arises in the middle surrounded by a large number of male flowers represented by stalked stamens ( <i>Poinsettia</i> , <i>Euphorbia</i> )	<i>Verticillaster</i> In this inflorescence, typical of plants with opposite leaves, a cyme arises in each leaf axil. The first axis ends in a flower. Two branches arise below it bearing branches in an alternating manner. Flowers are sessile and appear as a cluster ( <i>Ocimum</i> ) around the node.

See Fig. 30.7 and 30.8.

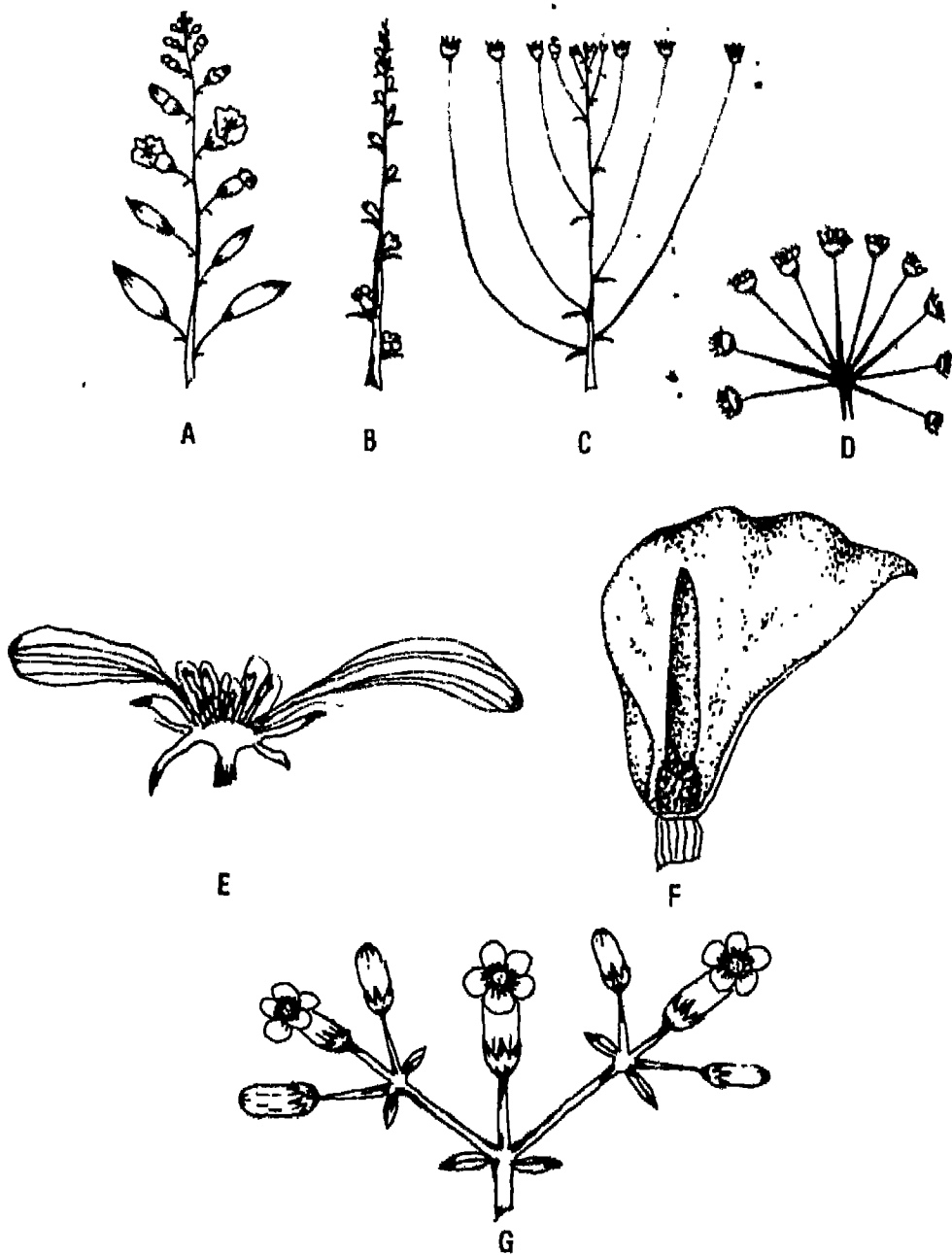
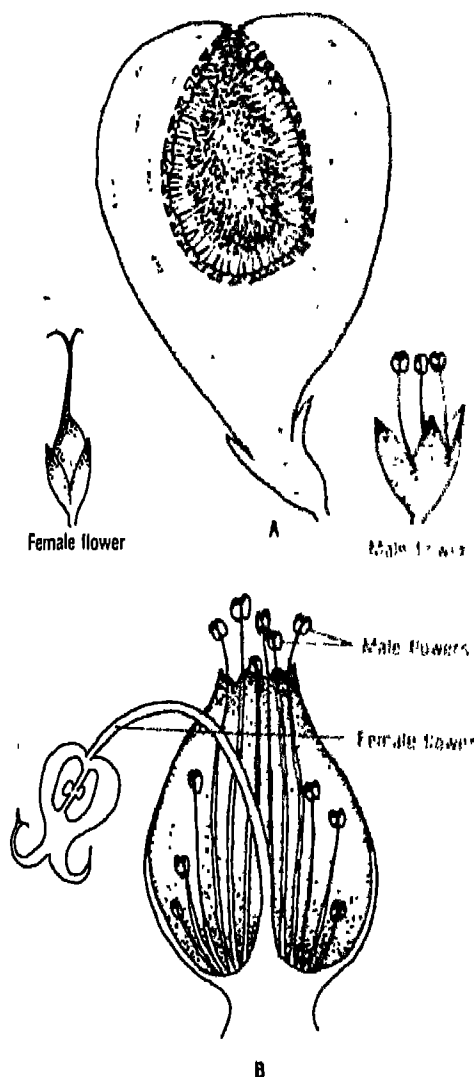


Fig. 30.7 A few types of inflorescence

A. Raceme; B. Spike; C. Corymb; D. Umbel; E. Head or capitulum (vertical section); F. Spadix;  
G. Dichasial cyme



**Fig. 30.8** Special types of inflorescence  
A. Hypanthodium (vertical section) and enlarged views of male and female flowers; B. Cyathium (vertical section). See Table 30.1 for details.

also some special types of inflorescence (see Table 30.1).

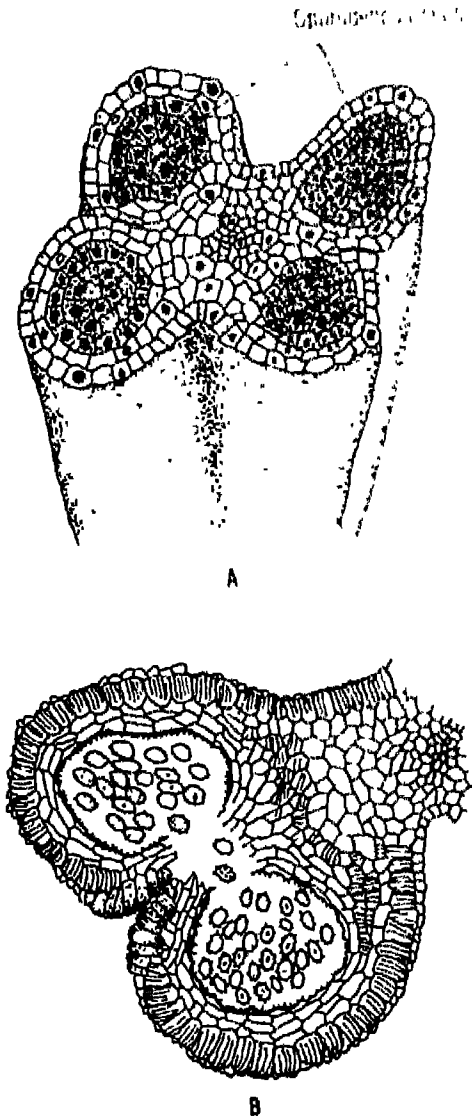
#### Functions of a Flower

The main functions of flowers are: (i) pro-

duction of pollen and egg, (ii) pollination, (iii) fertilisation, (iv) development of seeds and fruits (v) dispersal of seeds and fruits.

**Development of the Pollen or Male Gametophyte.** Pollen grains are produced in the anther. A very young anther consists of a mass of undifferentiated cells surrounded by an epidermis. During the development of the anther its outline becomes four lobed. Each lobe is termed a **MICROSPORANGIUM** (Fig. 30.9A) which contains a mass of cells characterised by their large size, abundant cytoplasm and prominent nuclei. These cells are called **SPOROGENOUS CELLS** or **MICROSPOROCTES**. As the anther grows the sporogenous cells undergo a few mitotic divisions to increase their number before they function as **MICROSPORE MOTHER CELLS**. Microspore mother cells contain two sets of chromosomes and are, therefore, diploid. Each microspore mother cell divides meiotically and gives rise to four microspores. The chromosome number is reduced by half (to one set) and the microspores are **HAPIOID**. Initially the four microspores remain enclosed in a common wall (tetrad condition).

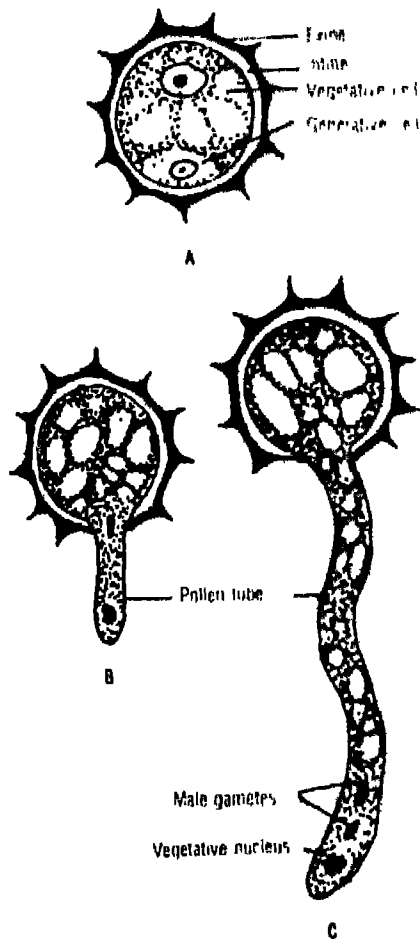
The individual microspores become separated. Each microspore enlarges and undergoes a mitotic division to form a large **VEGETATIVE CELL** (tube cell) and a small **GENFRATIVE CELL** (Fig. 30.10A). Once the vegetative and generative cells are formed, the entire structure which represents the male gametophyte is referred to as the **POLLEN GRAIN**. In a large number of flowering plants, pollen are shed at the two-celled stage (Fig. 30.10A). In some plants, the generative cell undergoes a mitotic division to give rise to two male gametes before the pollen grains are shed.



**Fig. 30.9** A. Diagrammatic view of a portion of young anther in cross section. Note the four microsporangia containing sporogenous cells.  
B. Portion of cross section of a mature anther

The wall between the two adjacent sporangia disintegrates and forms a pollen sac (Fig. 30.9B). At maturity each anther contains two pollen sacs. After the pollen grains are fully formed, the anther generally splits along the long axis to liberate them. The pollen grain is covered by a thick wall. The wall has two layers: an outer thick EXINE and an inner INTINE (Fig. 30.10A). As you have already learnt, the pollen grains that appear like dust particles reveal a wide range of microsculpturing of the exine in high magnification, under a scanning electron microscope. The exine is made up of a complex substance called SPOROPOLLENIN. This is one of the most resistant biological materials known. At one or more places, the exine is very thin or absent. These regions are known as GERM PORES through which the pollen tube emerges. The intine is comparable to the cellulose cell wall of any other cell. At the time of pollen germination, it protrudes through the germ pore and gives rise to the pollen tube (Fig. 30.10 B,C).

*Development of Ovule and the Female Gametophyte:* Ovules (which are the future seeds) are formed in the ovary in the early stages of flower development. In plants such as mango and cashew the ovary contains only one ovule. In poppy there are several thousand ovules and in orchids often more than one million. The ovule first develops as a projection on the placenta. It is composed of a multilayered cellular tissue called the NUCELLUS. A hypodermal (lying below the epidermis) cell of the nucellus enlarges and becomes transformed into a MEGASPORE MOTHER CELL (also called megasporocyte). As growth and development of the ovule proceed, the nucellus is raised on a stalk-like



**Fig. 30.10** Mature pollen and pollen germination  
A. Section of a pollen grain showing a thick exine, a thin intine and vegetative and generative cells; B, C. Growth of pollen tube. In C, two male gametes are seen.

structure called the **FUNICULUS**. It is also surrounded by one or two protective layers called **INTEGUMENTS**, leaving a small opening at one end termed the **MICROPYLE** (Fig. 30.11). This opening serves as a

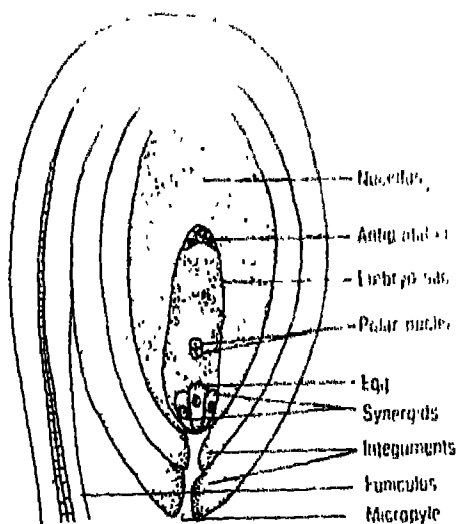
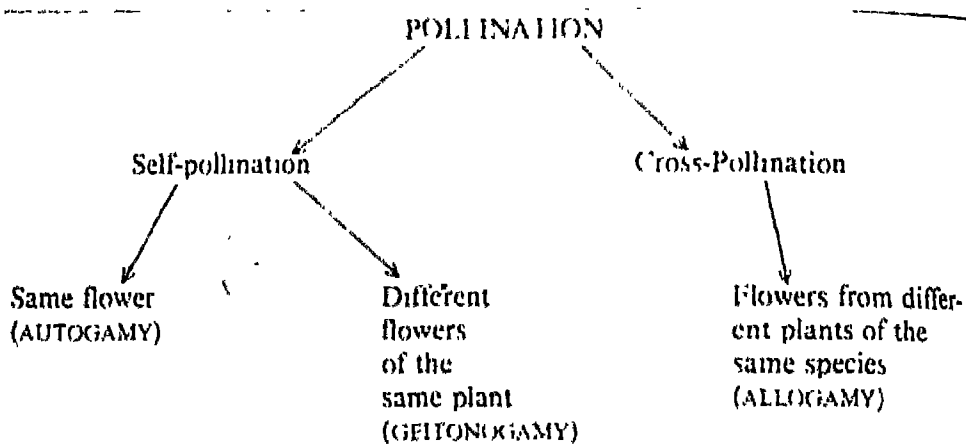
passage for the entry of the pollen tube into the ovule.

The diploid megaspore mother cell enlarges and undergoes meiosis to produce four haploid cells called **MEGASPORES**. Generally three megaspores degenerate and the remaining megaspore enlarges and its nucleus undergoes three successive mitotic divisions. As a result eight haploid nuclei are formed. The megaspore enlarges into an oval-shaped structure called the **EMBRYO SAC**, which now onwards is termed the **MEGAGAMETOPHYTE** (gamete bearing) (Fig. 30.11). The eight nuclei of the embryo sac arrange themselves into three groups. Three nuclei migrate toward the micropylar end of the embryo sac, other three move in the opposite direction (the chalazal end) and the remaining two nuclei are retained in the centre. Plasma membranes and cell walls then develop around all the nuclei excepting the two at the centre. The three cells at the micropylar end form the egg apparatus which comprises the **EGG CELL** and two **SYNERGIDS**. The three cells at the chalazal end of the embryo sac are called **ANTIPODAL CELLS**. The remaining two nuclei in the centre of the embryo sac (now called the central cell) are called **POLAR NUCLEI** which may fuse and form a diploid secondary nucleus. A fully developed embryo sac with the nucellus, integuments and funiculus, together constitute the mature ovule.

### Pollination

The term pollination refers to the transfer and deposition of pollen on the stigmatic surface of the flower. Different types of pollination occur in plants. (See the chart on p.492.)

Autogamy results when a flower is pollinated by its own pollen. An autoga-



**Fig. 30.11** Longitudinal section of an anatropous ovule with two integuments and micropyle. The embryo sac contains an egg, two synergids, three antipodal cells and two polar nuclei.

mous flower is always intersexual as the whole process occurs within its confines

(wheat, rice, pea, etc.). When pollen from one flower are deposited on the stigma of another flower borne on the same plant, the type of pollination is known as geitonogamy (= marriage between neighbours). In allogamy, pollen are from a different plant of the same species. Genetically both autogamy and geitonogamy result in self-pollination. Allogamy represents cross-pollination where genetic recombination is ensured.

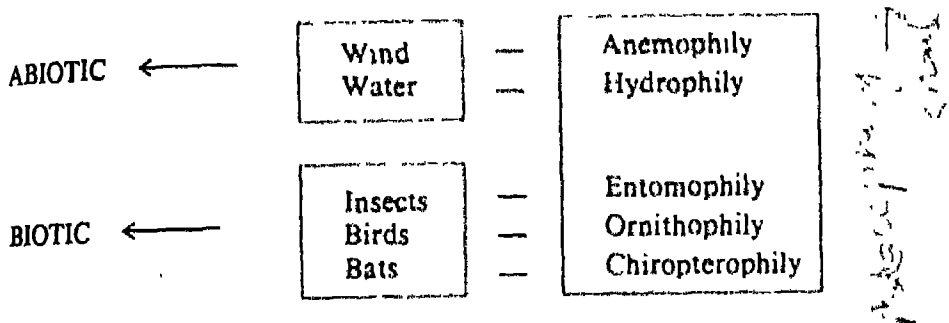
Cross-pollination requires an abiotic or a biotic agent (See the chart on p.493).

**Wind Pollination:** A large number of plants such as coconut palm, date palm, *Cannabis* (bhang), maize and numerous grasses are wind-pollinated. Anemophilous flowers are unisexual, with the anthers and stigmas exposed, and the pollen grains are small, smooth and dry. As there is much wastage, pollen are produced in enormous quantities. For example, a single flower of *Cannabis* produces over 5,00,000 pollen grains. Anemophily is not precise and is largely non-directional and involves movement of pollen over long distances. Great quantities of pine pollen (which are winged) have



## AGENCIES OF POLLINATION

## TECHNICAL TERMS FOR THE TYPE OF POLLINATION



been found hundreds of kilometres away from the nearest forests.

**Water Pollination:** True hydrophily, where the pollen grains are water-borne, is rare and occurs only in totally submerged marine plants like *Zostera marina*. This plant has elongated (2500  $\mu$ m), needle-like pollen grains without an exine. When they reach the stigma, they coil around it and germinate. In the submerged fresh water plant *Ceratophyllum demersum*, the male flower bears 30-45 stamens. The anthers abscise at the base, float to the surface of water, and dehisce there. The liberated pollen germinate and as they sink in water, they effect pollination of the female flowers.

In *Vallisneria*, the male flowers are

released to the surface of water, where they attach themselves to the stigma of floating female flowers held afloat by long stalks. Pollination occurs on the surface of water and after fertilisation the female flower is pulled down by the coiling of the flower stalk.

**Insect Pollination:** Insects visit flowers to gather nectar and pollen. Flowers advertise the availability of food rewards to the insects either by their showy colours or fragrance. Insect-pollinated flowers possess all the positive attributes of form, size, colour and scent, whereas flowers pollinated by abiotic agencies generally lack them. An insect visiting a flower inadvertently transfers pollen to another flower.

The flowers of the *Labiatae* (mint family) have a two-lipped corolla. The lower lip acts as a platform on which the bee alights. In *Salvia* there are only two stamens. Only half the anther is fertile, the sterile half forms a plate and partly blocks the corolla tube. Their fertile halves are sheltered in the upper lip of the corolla. The bee pushes the plate and the fertile halves of the anther swing onto the bee's back, dusting it with pollen. This is known as the 'turn-pike' or 'lever' mechanism.

Bees are the chief visitors of flowers and have pollen sacs (pollen baskets) to collect pollen. Many plants are pollinated by butterflies. Moths which generally visit flowers at night are active pollinators. For them, fragrance is the most important attractant.

**Bird Pollination:** Birds can derive only one staple food from flowers and it is nectar. The nectar is chiefly composed of sugars. It is reported that a humming-bird can take half its body weight of sugar in a single day. Birds visit such a variety of flowers (red silk cotton, coral tree, bottle brush) that it is difficult to define a typical "bird flower". Some of the bird-pollinated flowers have funnel-shaped corollas and produce copious amounts of nectar. Vivid colours, mainly red, yellow, orange and blue attract birds from long distances. Over 100 species of Australian plants have ornithophilous flowers.

**Bat Pollination:** Bats are nocturnal animals and the flowers they visit are large and have a strong scent. They move swiftly and transport pollen over long distances (30 km). The sausage tree, *Kigelia pinnata* is bat-pollinated. Generally, bat-pollinated flowers have more abundant nectar than ornithophilous flowers. They

generally have a large number of prominent stamens. For example, *Adansonia* (Baobab tree) has 1500-2000 stamens. Pollen are produced in large quantities.

Pollination is one of the essential functions of the flower. It is a pre-requisite for ensuring seed set and perpetuation of the species. Cross-pollination is also a means of bringing about genetic recombination and variation.

Mustard, safflower, sunflower, clovers, cucurbits, almonds and some of the pomeaceous fruit crops (having pome fruits) give significantly higher yields if bees are available for pollination. Adequate irrigation, fertilisers or cultural care given to such self-sterile crops would not increase their potential yields, if sufficient pollinators are not available during their flowering period.

**Growth of the Pollen Tube:** Pollen grains which fall on the stigma are held by its sticky secretion and start germination. In this process, a short cytoplasmic outgrowth called GERM TUBE emerges from the pollen and continues to grow as a pollen tube. The contents of the pollen grain move into the pollen tube. The vegetative nucleus usually moves to the tip of the tube followed by the generative nucleus (Fig.30.10). The pollen tube grows

Pollination is a most fascinating aspect of biology. A few instances of highly specific associations of flowers and pollinators have been recorded. Figs are a classical example that require insects of *Blastophaga* sp. to effect pollination. Several species of the orchid genus *Ophrys* require a moth. The flowers are shaped like a female moth and have the same texture, colour pattern and even smell. The male moths duped to believing that they are copulating with their females, bring about pollination. Interpretation of such a high degree of plant-insect interaction requires knowledge and understanding of several fields of science.

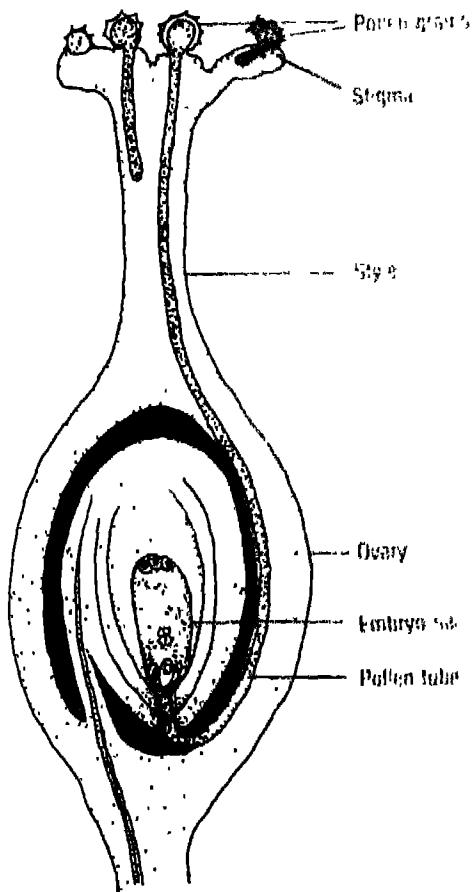


Fig. 30.12 Longitudinal section of a pistil showing pollen germination. One pollen tube has grown through the style and has reached the embryo sac through the micropyle.

through the tissues of the stigma and style and reaches the ovary (Fig. 30.12). During its growth the pollen tube secretes enzymes which hydrolyse (digest) reserve

food materials in the tissues of the stigma and the style and utilises them. The generative nucleus of the pollen tube divides mitotically and produces two male nuclei. The pollen tube eventually enters the ovule through the micropyle (Fig. 30.12) and discharges the two male gametes (sperms) into the embryo sac.

### Fertilisation

In the embryo sac, one of the two male nuclei fuses with the egg nucleus and forms a diploid ZYGOTE. This process of nuclear fusion is called SYNGAMY. The other male nucleus fuses with the two polar nuclei (or secondary diploid nucleus) and gives rise to a TRIPLOID nucleus called the PRIMARY ENDOSPERM NUCLEUS. This process of nuclear fusion is known as TRIPLE FUSION. The zygote later divides mitotically and produces a multicellular diploid EMBRYO. The primary endosperm nucleus divides and the resulting nuclei also undergo a series of divisions. Later cell walls develop around the nuclei to form a tissue called the ENDOSPERM (Fig. 30.13). Endosperm accumulates food reserves and functions as the nutritive tissue for the developing embryo. In some flowering plants the endosperm is cellular from the very beginning. Fertilisation involving the union of egg and one of the sperm nuclei and the fusion of the second male nucleus with the polar nuclei is unique to flowering plants and is described as DOUBLE FERTILISATION.

### Embryo Development

The zygote (Fig. 30.14 A) divides by a transverse wall to form two cells (Fig. 30.14B). Further divisions of these two cells give rise to a filament called the PROEMBRYO (Fig. 30.14C). Later the terminal cell of the pro-

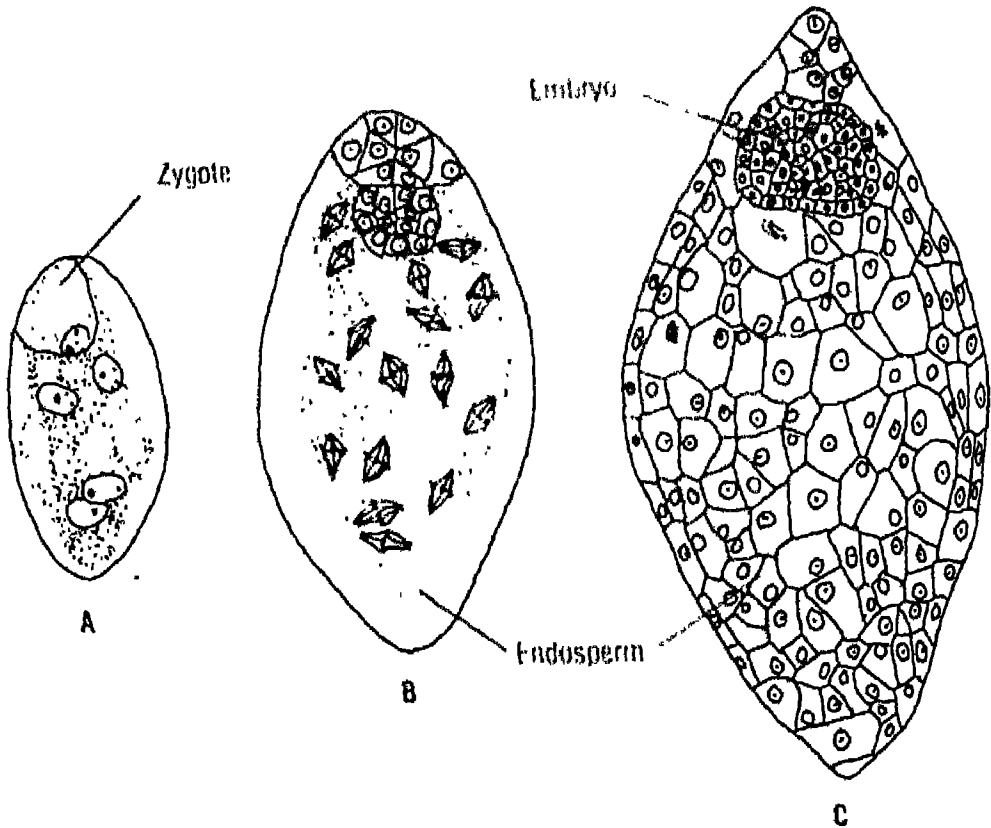


Fig. 30.13 Three stages in the development of nuclear endosperm in *Acalypha indica*. A,B. Free nuclear stages; C. The endosperm has become cellular. (After John and Kapil, 1953)

embryo undergoes a series of divisions in various planes to form the EMBRYO proper (Fig. 30.14 C-G). The remaining part of the filament is known as the suspensor. The suspensor pushes the developing embryo into the endosperm, enabling the embryo to absorb nutrients from the endosperm. Embryologists have

recognised several variations in early embryo development. The mature embryo consists of a short axis with one or two cotyledons (Fig. 30.14H). Only one cotyledon develops in the monocotyledons while two cotyledons are characteristic of dicotyledons. You can now appreciate the significance of the terms *mono* and

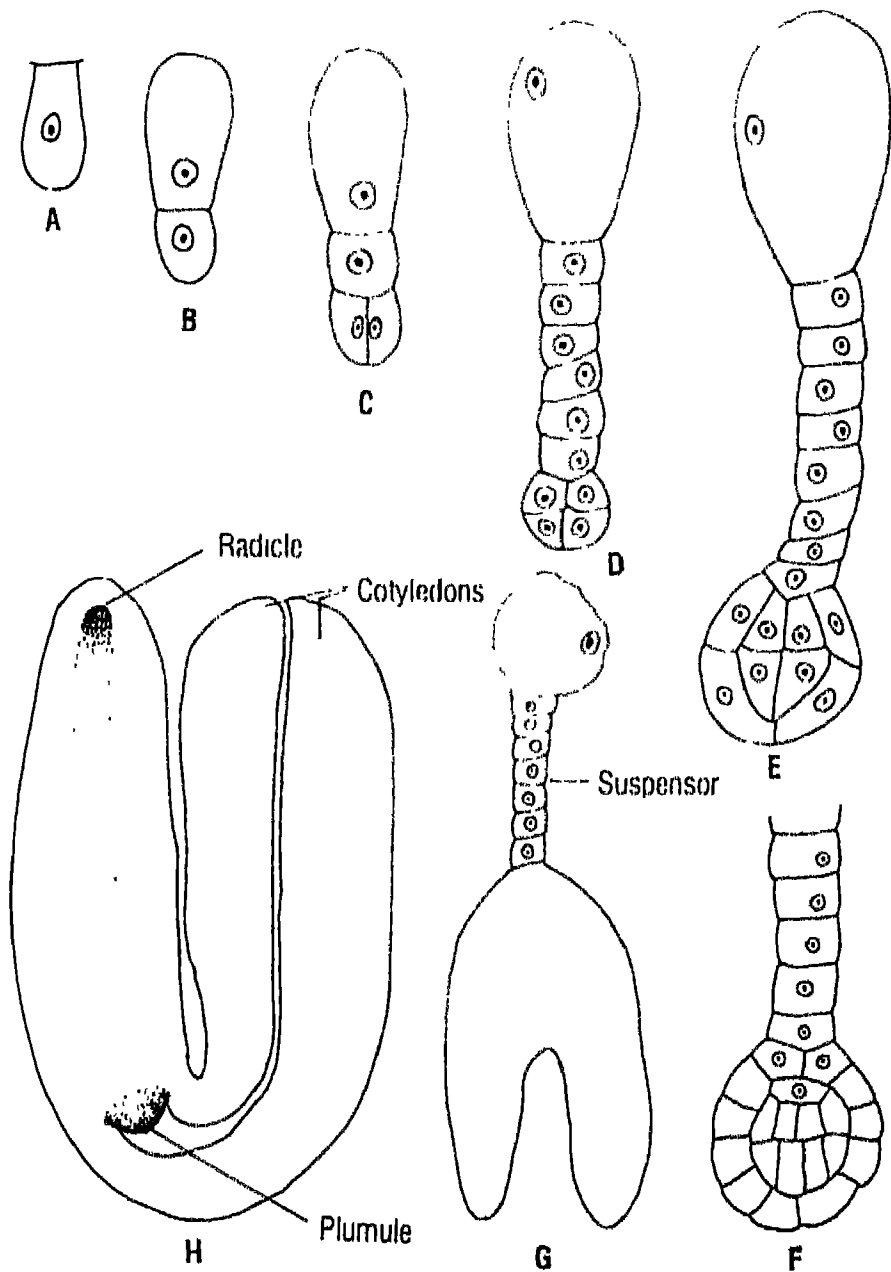


Fig. 30.14 Stages in the development of embryo in *Capsella bursa-pastoris*

di cotyledons. The embryonal axis possesses the PLUMULE at the apical end which gives rise to the shoot and the RADICLE at the basal end, which develops into the root system.

The presence of seed is unique to gymnosperms and angiosperms. The integuments of the ovule develop into the hard SEED COAT. This protective coat ensures survival of the seeds. The surrounding ovary becomes transformed into a fruit.

### Fruit

It is not easy to define a fruit. In common language it denotes a sweet, juicy or pulpy, coloured, aromatic structure that encloses seed(s). Oranges and apple fit this description. Botanically any ripe ovary is called a true fruit, whether it is cucumber, tomato, pea or coconut. However, other floral parts may also take part in fruit formation. For example, in apple (Fig. 30.15A) and fig the main edible portion of the fruit is the fleshy receptacle. Such fruits are called false fruits. A few representative fruits are shown in Fig. 30.16.

The wall of a true fruit is called pericarp. It is divisible into three zones. In the ripe mango (Fig. 30.15B), the outer skin is the epicarp. The sweet, edible flesh is the mesocarp and the innermost hard zone that encloses the seed is the endocarp. The nature of these three zones varies in different fruits. In dry fruits, the pericarp is papery or woody and is not easily distinguishable into three zones.

Pollination stimulates the ovary to grow. It is essential for fertilisation and for seed development. Pollination also prevents ovary abscission. Pollen grains contain small amounts of auxin, which together with a limited amount of additional auxin from the carpellary tissues can support the initial growth of the ovary.

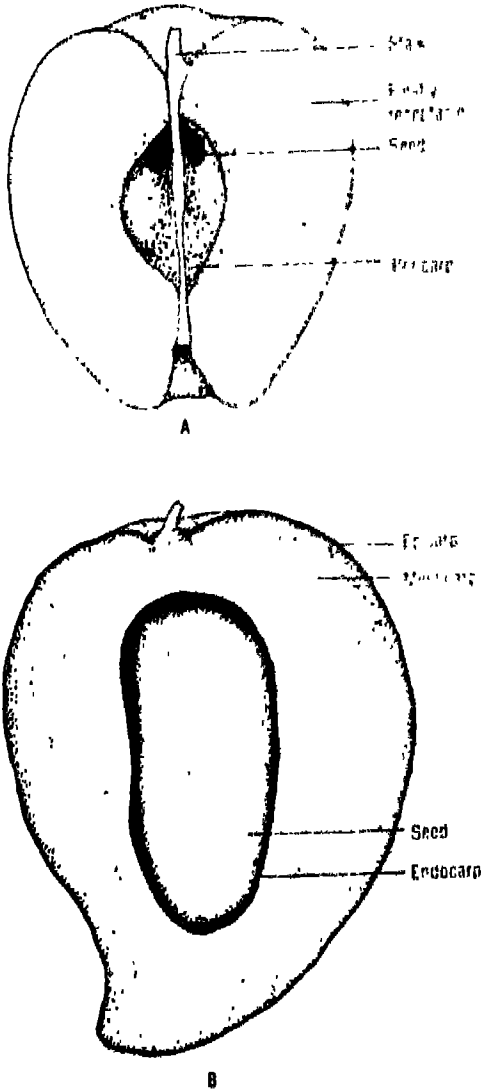
Subsequent fruit growth requires normal seeds which synthesise auxins, gibberellins and cytokinins. Thus, seeds play a key role in fruit development.

When an ovary develops into a fruit, cell division, expansion and differentiation are involved. A pumpkin ovary shows a 20-fold increase in size just in two weeks time.

Some plants are able to form fruits without fertilisation. Such fruits are called parthenocarpic fruits. Parthenocarpic fruits are either seedless or contain empty or non-viable seeds. Most cultivated varieties of banana are parthenocarpic. Seedless grapes, oranges, and water melons have been developed by horticulturists.

Fruits are a source of sugars, pectin, organic acids, vitamins and minerals. They have been eaten by people from very ancient times. They also form an important item of food for animals. Why does a plant invest so much of its food in the production of fruits? The fruit protects seeds against hostile climatic conditions and animals. It aids in the dispersal of seeds to distant localities through wind, water and animals.

Angiosperms exhibit a wide variety of fruits. Broadly, the fruits are classified into three kinds. A SIMPLE FRUIT is one in which ovary takes part in development. The fruit may be fleshy or dry, dehiscent or indehiscent (bean, mustard, mango, citrus). In an AGGREGATE FRUIT each free carpel develops independently to form a bunch of fruits (*Michelia*, strawberry, custard apple). A COMPOSITE FRUIT develops from an inflorescence by the fusion of flowers and their parts (pine-apple, Fig. 30.17). The study of fruits is important to understand the taxonomy, distribution, adaptation, evolution and utilisation of plants. POMOLOGY is a



**Fig. 30.15** A. Vertical section of an apple. The edible portion of the fruit is the massive receptacle; B. Vertical section of mango. The edible, fleshy mesocarp is surrounded on the outside by a thin epicarp. Inside the mesocarp lies the hard endocarp enclosing a seed.



**Fig. 30.16** A few representative fruits, some of which are commonly termed vegetables (Photo : Dr B. Hari Gopal and Dr M. N. B. Nair)

branch of horticulture that deals with the study of fruits and their cultivation.

The range of seed number, size, weight, shape, colour and texture is extremely varied. Likewise, fruits also exhibit a wide spectrum of form. The morphology of seed and fruit is an important criterion for classification and phylogeny of plants.

### *Dispersal of Seeds*

As seeds contain the miniature but dormant future plant, their dissemination is crucial for the distribution and establishment of plants over a wide geographical area. As with pollen grains, the principal agents of seed dispersal are wind, water and animals. Seeds of many plants are suf-



Fig. 30.17 A composite fruit of pineapple  
(Photo :Dr B. Hari Gopal and Dr M.  
N. B. Nair)

ficiently light to be carried to great distances by wind currents. Wind dispersed seeds usually have wings or tufts of hairs which make their movement in air easy. Some seeds and fruits are carried to long distances by water before they develop into new plants. Fruits are eaten by animals such as birds and the enclosed seeds may be taken to distant places before they are passed out in their excreta without any damage to the embryo. Some seeds possess spines or hooks which enable them to stick to the body of animals and are carried from one place to other. Finally, man

himself is a great disseminator of seeds, especially of economically important plants. People have not only deliberately introduced seeds from one corner of the world to another but continue to buy choicest seeds from other countries.

Seeds are enigmatic structures of the living world. They are the principal means of perpetuation of the species. A seed consists of a part of the parent plant (ripened ovule) enclosing the rudiment of the next generation (embryo). Seed is the means by which the new individual is dispersed. Occasionally the pericarp or other floral organs may be associated in constituting the dispersal unit (cereals, bamboo, sunflower, etc.). Seeds account for 70% of all food consumed by humans and a large proportion of the remainder is derived from animals fed on seeds. Production of good seeds has been the main goal of agriculturists to meet growing needs of increasing populations, end hunger and assure peace. Our knowledge of seed biology has enabled us to use seed banks for genetic conservation. You will learn more about this aspect later.

### *Structure of the Seed*

All seeds have certain common features: an embryo, stored food and protective coverings. The zygote which results from syngamy is the first cell of the embryo. Although an embryo is formed by a series of rapid cell divisions of the zygote and its products, it is very rarely that an embryo straightway produces a plant. In a majority of plants the embryo ceases to grow and lies dormant within the seed. This unusual phenomenon is not fully understood but has given seed plants several advantages for survival. Therefore the seed represents neither the beginning nor the end of plant growth but a stage in between.



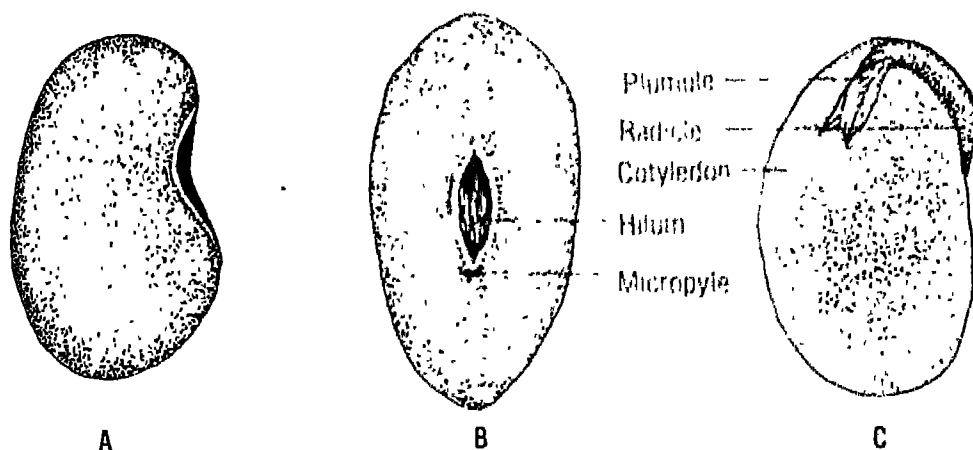


Fig. 30.18 A, B. Lateral and ventral views of lima bean, C. Embryo with seed coat and one cotyledon removed to show the radicle and plumule

We shall now examine the structure of a bean seed (Fig. 30.18). It is attached to the fruit by short stalk called the **FUNICULUS**. At maturity the funiculus becomes detached, leaving a scar, the **HILUM**, on the seed surface. Adjacent to the hilum is a small pore, the **MICROPYLE**. The bean seed has two seed coats that develop from the two integuments of the ovule. The outer seed coat is called the **TESTA**. In bean it is smooth, thick and variously coloured. The inner coat is thin, white and often difficult to separate from the testa. Soaking the seed in water for a few hours makes it easy for removing seed coats.

When the **SEED COATS** are removed, the large embryo comes into view. The bulk of it consists of a pair of fleshy structures called **COTYLEDONS**. These are the organs

in the bean seed that store carbohydrates and protein and provide nourishment to the developing embryonal axis. The cotyledons are attached laterally to the embryonal axis which has two parts, the **RADICLE** or the embryonic root and the **PLUMULE** or the shoot tip (Fig. 30.18). The shoot apex is enclosed within the first pair of small, folded true leaves. The region of the embryonal axis between the radicle and the point of attachment of the cotyledons is called the **HYPOCOTYL** (below the cotyledons) whereas the portion between the plumule and cotyledons is termed **EPOCOTYL** (above the cotyledons). In the bean seed both epicotyl and hypocotyl elongate rapidly when the seed germinates. The bean seed lacks endosperm and stores its reserve food in the cotyledons.

Seeds that do not contain endosperm at maturity are called NON-ENDOSPERMOUS SEEDS (groundnut, pea, mustard etc.). In plants such as the castor bean, rubber, cereals and coconut, food is mostly stored in the endosperm. In these seeds endosperm persists and nourishes the seedling during its early development.

The structure of maize as an example of a monocotyledonous, endospermous, seed is shown in Fig. 30.19.

As a matter of fact, a maize grain is a large single-seeded fruit in which the seed coat is fused with the fruit wall. As seen in a longitudinal section, the embryo lies on one side of the massive starchy endosperm. The endosperm is surrounded by a sheath of special tissue called ALEURONE LAYER. Cells of this layer contain proteins and play an important role in germination. The embryo consists of a single cotyledon which is much reduced and modified. It is attached laterally to the embryonal axis and is called the SCUTELLUM. This cotyledon has a secretory epidermal tissue that has direct contact with the endosperm. The region of the embryonal axis that points downward from the point of attachment of the cotyledon is the radicle. It is covered by a protective sheath called the COLEORHIZA. Above the point of attachment of the cotyledon, the embryonal axis becomes the PLUMULE, which is surrounded by a leaf-like covering called the COLEOPTILE.

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**Activity:** Dissect out soaked seeds of pea, water melon, castor, onion and rice and understand the structure and position of various parts.

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### *Seed Dormancy*

Seeds of most land plants have a low water

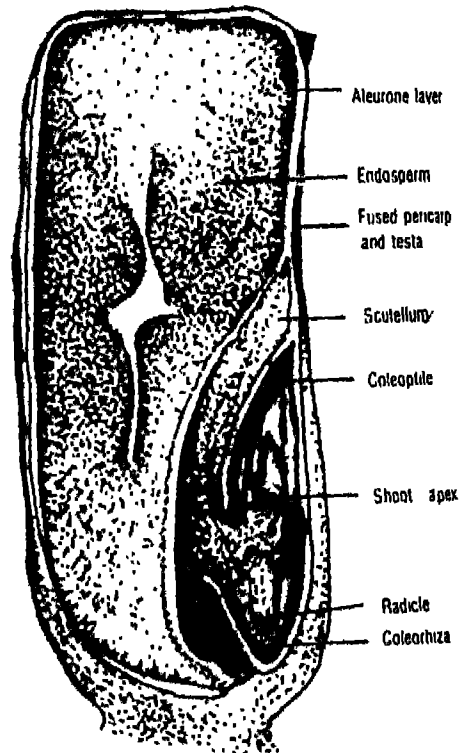


Fig. 30.19 Vertical section of a maize grain showing starchy endosperm, scutellum and embryo

content and exhibit virtually no metabolic activity. They consequently represent resting structure. Such QUIESCENT seeds can live for many years but germinate when soaked in water under a suitable temperature and in the presence of oxygen.

Also, seeds of many domesticated plants such as pea, bean, maize and rice can germinate immediately after they are harvested. In many other plants freshly harvested seeds are incapable of germination even under favourable conditions. There exists within the seeds some

block(s) that must be removed or overcome to allow germination to proceed. Such inactive seeds are called **DORMANT**. Removal of dormancy requires exposure to specific environmental factors or certain metabolic changes within the seeds.

Seed dormancy may be traced to several causes. One of these is the presence of a hard and impermeable seed coat (and other coverings) which prevents the entry of water and oxygen. Under natural conditions, the coat-imposed dormancy is gradually overcome by the weakening of seed coat. In some seeds the hard seed coat is softened by enzymes while passing through the digestive tract of fruit-eating birds or other animals. Seed coats may also be broken down by soil microorganisms or by mechanical abrasions in the soil. Scratching the seed coat (scarification) has the same effect.

Presence of certain inhibitory substances such as abscisic acid (ABA), coumarin, phenolic acids, short-chain fatty acids in the embryo, endosperm or

other tissues of the seed or fruit is another cause for seed dormancy. As long as the concentration of the inhibitory substance is high the seed remains dormant. The concentration of these inhibitory substances can be reduced artificially by exposure to alternating temperature, chilling, light, placement in running water or treatment of hydrated seeds with oxygen, nitrate, nitrite, thiourea, gibberellins, cytokinins and ethylene.

You might wonder why dormancy should operate when the function of a seed is to produce a plant. Seed dormancy is an adaptation to ensure seed germination only under favourable conditions thus enabling successful establishment of the seedlings. It offers several benefits. It enables seeds to be disseminated in time and space and helps them to germinate when environmental conditions are most favourable. Germination of different seeds occurs in specific situations and seasons. Seeds can be artificially stored to ensure agricultural security.

## SUMMARY

Continuous production of new individuals is necessary for the perpetuation of any species. Reproduction in plants is accomplished by the fusion of gametes (sexual reproduction) or even without it (asexual reproduction).

Plants are unique because parts of stems, roots and leaves are capable of regenerating into whole new plants. Thus vegetative propagation occurs naturally in many wild and domesticated plants. It is also practised by people to multiply economically important plants. Grafting is a technique in which a shoot or a part of the plant (scion) is inserted into another plant (stock) so as to be nourished by it and united with it. The maintenance of purity of a given variety of plants by vegetative propagation is called cloning.

In angiosperms sexual reproduction occurs in the flower, which is considered as a specially modified shoot. In a flower the sepals are generally green and protect the other floral organs. The petals are usually coloured, showy and often fragrant and serve to attract pollinators. The stamens and carpels are the male and female reproductive structures respectively. In each stamen the anther contains four microspo-

rangia which produce a large number of pollen grains. The pistil has three parts; the basal swollen part the ovary, bears ovules. The tip of the ovary is elongated into a style that ends in a stigma. It is the stigma that acts as a receptive structure for the pollen.

Within each ovule a haploid embryo sac usually containing 8 nuclei is formed. Of these one nucleus develops into the egg by acquiring cytoplasm and a wall around it.

The process by which pollen are transferred to the stigma is called pollination. Depending on the distribution of sex organs in the flower(s) and their time of maturity, the pollen received by the stigma may be from the same or a different flower, borne on the same or another plant. Wind, water, insects, birds, bats and other animals act as pollinating agents.

The pollen grains deposited on the stigma germinate to form pollen tubes which penetrate the style. One pollen tube enters the embryo sac and releases two male gametes. One male gamete fuses with the egg to form the zygote (syngamy) and the other fuses with the two polar nuclei in the middle to give rise to the endosperm. This is called double fertilisation and occurs only in angiosperms.

The ovule develops into a seed. The zygote forms the embryo, the endosperm or cotyledon (s) stores food reserves and the integuments contribute to the formation of the seed coat. The ovary matures into the fruit. The size, shape and colour of fruits and seeds vary enormously and there are various strategies adopted by plants to disseminate them.

A seed is an enigmatic structure. The moisture content and metabolic activity are very low in seeds and they can remain dormant until the conditions are favourable for their germination.

There are several causes of seed dormancy, including hardness of seed coat and presence of inhibitory substances. Dormancy may be overcome by various methods. Seeds can be stored artificially to ensure food security as well as to use them for raising crops in the next season.

As seed and fruit set are crucial events in crop production, sexual reproduction, especially pollination biology is an important subject of study.

## QUESTIONS

Tick mark (✓) the correct answers :

1. The most significant value of vegetative propagation is that:
  - (i) it enables rapid production of genetic variation
  - (ii) it is a means of producing a large population of individuals genetically identical to the parent
  - (iii) it ensures that the progeny are safe from attack of diseases and pests
  - (iv) it is an ancient practice.
2. Listed below are a few economic plants. Write against each of them, the principal organ/part/method used for propagation
  - (i) Wheat .....

- (ii) Onion
- (iii) Gladiolus
- (iv) Sweet potato
- (v) Bryophyllum
- (vi) Grapes
- (vii) Mango
- (viii) Jasmine
3. What are the advantages of using plant tissue culture for propagation?
4. Name *one* example for each of the following:
  - (i) A plant in which both male and female sex organs occur in the same flower
  - (ii) A plant in which separate male and female flowers are borne on the same individual at different positions
  - (iii) A cultivated plant in which neither fruits nor seeds are formed
  - (iv) A species in which the individual plant is either male or female
5. What is the basic difference between a racemose and a cymose inflorescence? Differentiate among spike, umbel, corymb and head with suitable examples.
6. What are characteristics of wind pollinated flowers?
7. Match the items in column A with appropriate items in Column B:

*Column A*

*Column B*

Zygote

*Vallisneria*

Parthenocarpy

Sunflower

Bird Pollination

Ground nut

Hydrophily

Embryo

Capitulum

Edible banana

Non-endospermous seed

Red silk cotton

Apple

8. In what ways does the study of pollination enrich our understanding of biology and enable us to apply it for increasing crop productivity?
9. Explain the biological and economic importance of fruits.
10. In what sense are seeds a physiological enigma?
11. By means of labelled diagrams *only* bring out the essential differences in the structure of a dicotyledonous and a monocotyledonous seed.
12. What is the ecological significance of seed dormancy?



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## GROWTH AND DEVELOPMENT OF FLOWERING PLANTS

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IN common parlance the term 'growth' may be applied to several things and situations. It is not uncommon to hear people talking of growth of cities, of weeds, of a tradition, of indiscipline, of a legend, or even of baldness. You might have actually seen the growth of crystals of sugar or salt in the laboratory. What is the meaning of growth when used in biology?

### Characteristics of Plant Growth

GROWTH, one of the most fundamental and conspicuous characteristics of living organisms, is the sum total of various processes that combine to cause an irreversible increase in mass, weight, or volume. In multicellular plants growth is generally accomplished by the assimilation and fixation of inorganic substances from the surrounding environment. For growth to occur the rate of synthesis of complex molecules like proteins and carbohydrates must exceed their breakdown. Plant growth occurs by cell division and cell

enlargement. Increase in the number and size of cells by itself cannot account for the development of an organised plant. For example, when a seed is sown, it does not become a larger seed but a seedling. Thus growth is invariably accompanied by differentiation, which is explained as qualitative change in terms of structure and function of cells. Although all the individual cells in a plant have the same genetic information and are influenced by the same external factors, they come to perform different functions, depending on where they become located in the mature plant. The internal cellular mechanisms block the expression of certain genes and allow that of certain others.

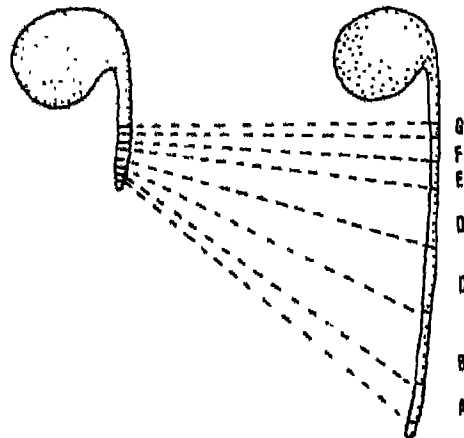
Differentiated cells can be observed in tissue preparations under a microscope. Structurally these modifications may involve changes in shape (tracheids), loss of end walls (vessels), perforation of end walls (sieve cells) and impregnation of suberin (cork cells) and accumulation of

latex (laticifers) or silica. However, the precise mechanism by which differentiation is regulated in cells at specific time and location in a plant is not completely understood.

Cell division and differentiation are important aspects of growth and development in both plants and animals. In a mammal it is difficult to specify the regions where growth occurs. Embryonic growth in an animal is completed quite early, although the mature size may be reached at specific periods. Plants, especially trees, are constructed in a modular fashion. That is, their development is relatively open-ended and their structure never complete. In a perennial, new organs are formed and old ones replaced. Cell division continuously occurs in the meristems. Cell division without enlargement would result in an increase in the number of cells, but with a progressive decrease in the size of individual cells. As the cells cease to divide they increase in size. Cell enlargement manifests itself in the visible signs of growth—increase in size and weight of the organ or the whole plant. You have already learnt in Chapter 26 (Fig. 26.44) that in the root meristem, the zone of elongation or enlargement lies just behind (proximal) the meristematic zone. Eventually the cells organise themselves into various primary tissues in the zone of differentiation. The three zones are not very clearly distinguishable in the shoot apex due to the development of leaf primordia.

**Activity 1:** Germinate some bean seeds till the radicle is about 2 cm in length. Blot the seedlings to remove surface water and mark the root at 2 mm intervals from the tip backwards with a waterproof ink. After the ink has dried, place the seedlings

on moist blotting-paper in a petri dish and allow them to grow (Fig. 31.1). Observe the position of the ink marks after 24 hours. Measure the intervals between the marks. What do your measurements indicate?



**Fig. 31.1** Detection of zones of elongation by the parallel-line marking technique. On the left is the seedling at the time of marking. On the right is the seedling after 24 hours growth. Zones A, B, C and D immediately behind the apex have elongated most.

When does growth occur and at what rate? Given suitable conditions, unicellular organisms can multiply continuously, doubling at fixed intervals of time. However, when a culture is prepared in a lim-



ited amount of nutrient medium, growth is slow in the initial stages due to the small number of cells (LAG PHASE). However, in a short time the number increases rapidly (EXPONENTIAL PHASE OF GROWTH). When the nutrients become limiting, growth slows down (STATIONARY PHASE) (Fig. 31.2). If the number of cells is plotted against time, a typical sigmoid or S-shaped growth curve is obtained (Fig. 31.2). A similar growth curve is shown by individual plant parts.

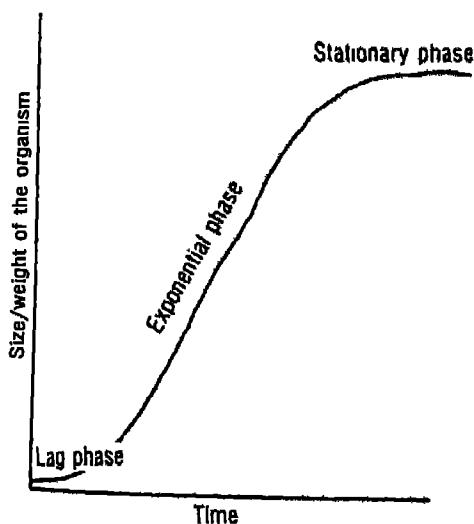


Fig. 31.2 The sigmoid growth curve. This curve is characteristic of single cells, suspension cultures, tissues, organs, organisms and populations.

**Activity 2:** Measure the length of a whole leaf of wheat or any other cereal or the diameter of a tomato fruit, starting from

the time it is tiny and just visible. Take daily readings and plot your results on a graph paper. What sort of curve do you obtain ?

Animal development follows a well-defined pattern. The animal body is compact and individuals of a species resemble one another rather closely. In a mammal the young animal generally looks like a miniature version of the adult. In angiosperms the freshly formed seedling cannot be called a miniature plant as it does not resemble the adult. In a tree some parts die and disintegrate while other parts continue to grow. The height, the number of branches, their orientation, the number and shape of leaves vary markedly from plant to plant even within a species. No two mango trees look exactly alike.

Growth in perennials continues throughout their life. However, in a calendar year the periods of active growth may be interrupted by periods of dormancy. Plants keep track of the time of year, the length of day and night, the direction of light, and gravity, and respond to these stimuli in various ways. In colder months, plant metabolism slows down and the plants become dormant. A dormant plant resumes growth when the environmental conditions become favourable. The part of the year when the plant shows maximum vegetative activity is called the growing season. The length of the growing season varies with the species, geographical location, the climatic conditions prevailing at the time and availability of water and nutrients. You have learnt of growth rings in trees. These are indications of the cyclic nature of the periods of dormancy and active growth. Trees growing in temperate and subtropical regions with marked seasonal changes in growth

show well-defined annual growth rings, but those growing in the more equitable climate of the tropics may not show such distinct rings. Some trees may produce more than one ring in a year, indicating more than one flush of growth per year.

Besides having a distinct growing season, plants also have a flowering and fruiting season when reproductive growth occurs. The onset and continuance of these complex processes during development of a plant are controlled by environmental factors, heredity, metabolism and internal signals.

### Growth Regulators

In all plants there occur minute quantities of certain chemical substances that regulate growth and differentiation. These substances are called PLANT GROWTH REGULATORS or PHYTOHORMONES (see Box). Phytohormones can have a positive effect on a process and thus promote it, or they may have a negative effect and cause inhibition. A particular hormone may promote certain processes, inhibit some others, and not affect many others. In general, developmental processes are controlled by more than one growth regulator, acting synergistically (cooperative and beneficial) or antagonistically (acting in opposition) with one another.

### Auxins

In the last sixty years or so a large number of growth regulators have been isolated from plants and their action studied. The first indication of their existence came from the work of Darwin (1880), who was studying the bending of the coleoptile of a grass (*Phalaris* sp.) toward light. He was able to establish that it was the tip of the coleoptile which was able to perceive the light stimulus. The latter was transmitted

to the subapical region (Fig. 31.3) where differential growth caused bending. Subsequently Boysen-Jensen (1913) was able to show that the stimulus could be transmitted through agar blocks but not through pieces of mica (Fig. 31.4). Some years later Went was able to demonstrate the presence of a substance which could diffuse into agar blocks. He also made the important finding that the substance always moved from the tip (or apex) toward the base of coleoptile. Agar blocks containing the diffused substance when placed on decapitated coleoptiles could induce the action of the tips (Fig. 31.5). He called this substance AUXIN (from the Greek word 'auxein' to grow). Curiously enough, the first auxin was isolated from human urine. Presently the term 'auxin' is applied to INDOLEACETIC ACID (IAA) and to natural and synthetic compounds having similar structure and growth regulating properties.

IAA, the principal natural auxin, has been found in all plants studied so far and fungi. The usual sites of auxin synthesis are meristems and enlarging tissues. It also occurs in the human urine, especially in persons suffering from pellagra (niacin or nicotinic acid deficiency). The role of IAA in humans is not known.

Functions of IAA: Auxin promotes elongation and growth of stems and roots and enlargement of many fruits, by stimulating cell walls to stretch in more than one direction. Auxin promotes cell division in vascular cambium. The reactivation of cambium in the growing season is apparently triggered by IAA moving from the developing shoot buds. Auxin also pro-

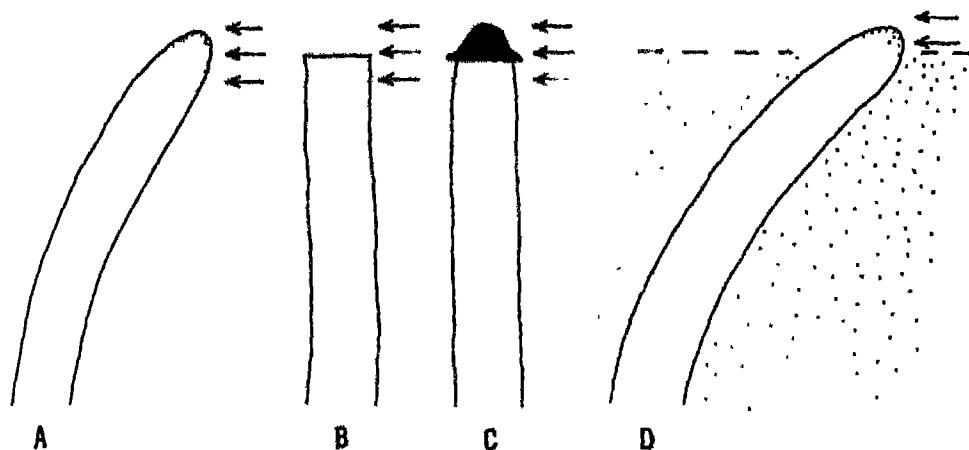


Fig. 31.3 Darwin's experiment with the seedlings of canary grass. A. When the tip of the coleoptile (a sheath that encloses the plumule) was exposed to unilateral light (see the direction of arrows) the coleoptile bent towards light; B. No curvature occurred when the coleoptile tip was excised; C. Placing an opaque cap on the tip of the coleoptile also prevented curvature; D. Curvature occurred when the seedling was buried in fine black sand excepting the extreme tip of the coleoptile.

motes root initiation. It causes the development of callus (a mass of parenchymatous cells without organisation) in tissue cultures.

In most plants the terminal bud at the apex of a shoot suppresses the development of lateral buds into branches. This phenomenon is termed APICAL DOMINANCE. Lateral buds start developing into branches when the apical bud is removed (Fig. 31.6). The process can be reversed if IAA is applied to the decapitated apex.

Apical dominance is thus under the control of auxins.

Another inhibitory effect of auxin is on ABSCISSION of leaves and fruits, which leads to leaf fall and fruit drop. Leaves and fruits must produce auxin continuously to prevent the formation of the abscission zone which cuts off their nutrient and water supply. Leaves are shed seasonally because they stop producing auxin.

Uses of Auxin: A large number of synthetic

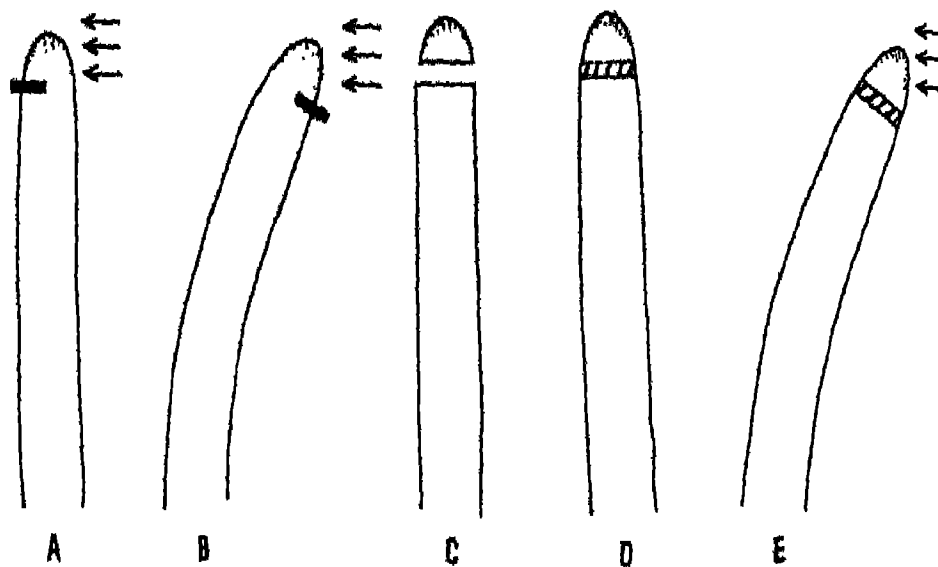


Fig. 31.4 Boysen-Jensen's experiment. A piece of mica inserted on the shaded side prevented curvature of the coleoptile (A) but not when it was inserted on the illuminated side (B). When the tip was removed (C) but was put back with a block of gelatine (D), normal phototropic curvature occurred (E).

auxins are presently being used in agriculture. 2,4-dichlorophenoxyacetic acid (2,4-D) is used to destroy broad-leaved weeds. 2,4-D does not affect mature monocotyledonous plants. Naphthaleneacetic acid (NAA) and indole butyric acid (IBA) are used for inducing the rooting of cuttings, particularly the woody ones. Foliar spray of NAA and 2,4-D causes flowering in litchi and pineapple. Auxins have been used to prevent premature fruit drop. The methyl ester of naphthaleneacetic acid is used to prevent the sprouting of potatoes. Synthetic auxins have also been misused by people. Large-scale aerial application

of defoliants used in Vietnam to expose the forests exterminated the wild relatives of economically useful plants such as citrus.

#### *Gibberellins*

The effect of gibberellins had been observed over a century ago. Japanese farmers had noted that certain rice seedlings grew excessively tall and spindly and toppled over before seeding. This condition was termed *bakanae* (in the Japanese language) or 'foolish seedling disease'. In 1926 Kurosawa discovered that the causal organism was a fungus.

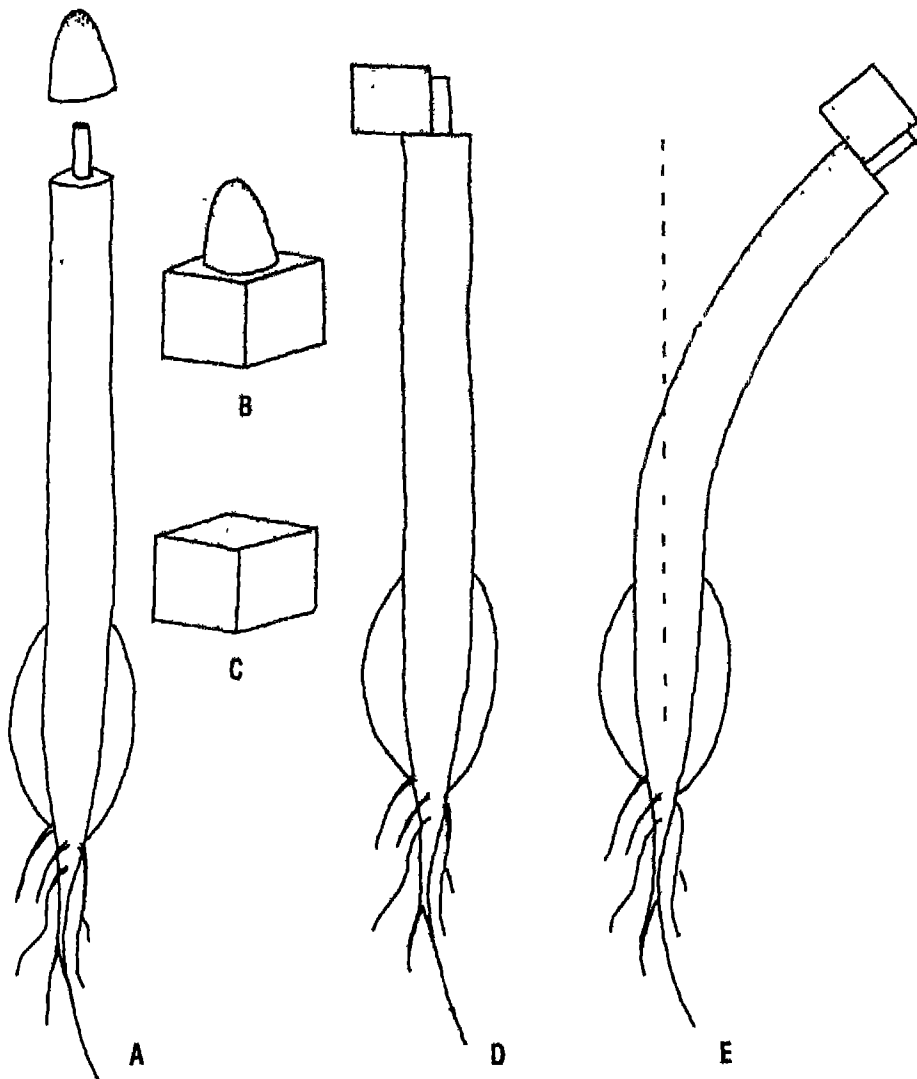


Fig. 31.5 Went's experiment on the demonstration of auxin production in the tip of oat (*Avena*) coleoptile. A. When the tip of the coleoptile was cut off, no auxin was available for the remainder of the coleoptile to elongate. B. Excised tip of coleoptile was placed on a cube of agar. C. Auxin diffused into the cube (stippled). D. The coleoptile tip was removed and the agar block containing auxin was placed on one side of another decapitated coleoptile. Auxin moved down the coleoptile directly below it, and caused greater elongation of cells along that side of the coleoptile than on the opposite side. Curvature was caused by differential growth rates on the two sides.



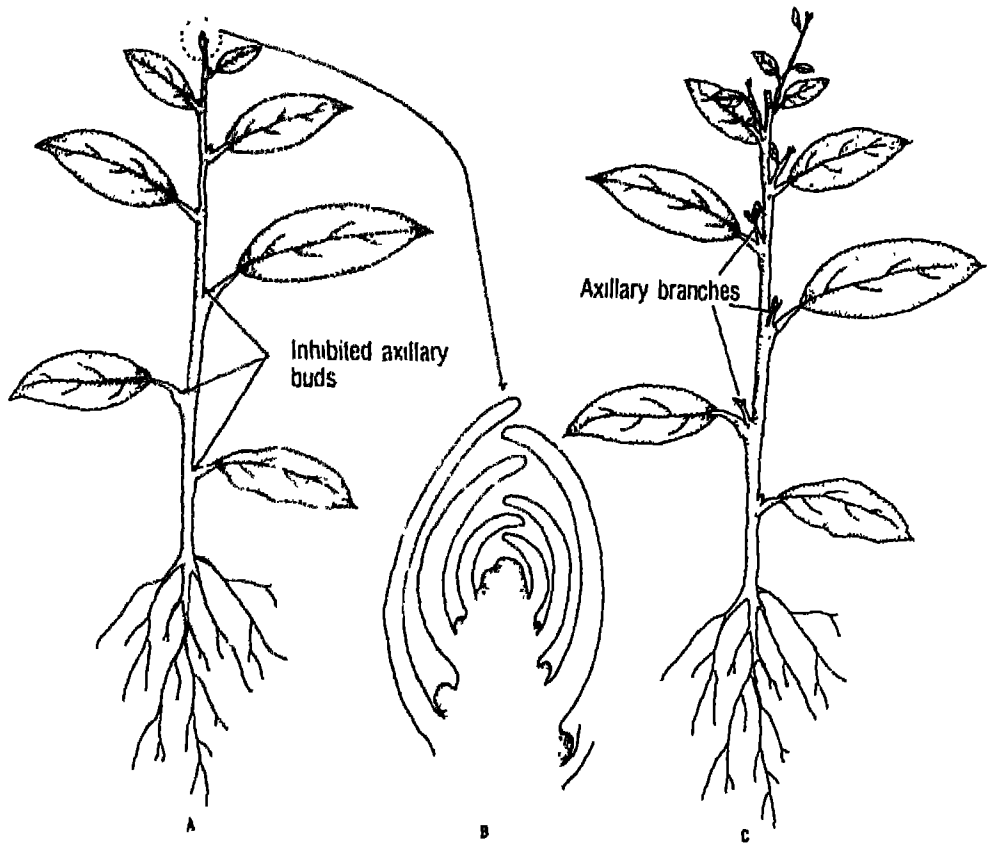


Fig. 31.6 Apical dominance in plants. A. The presence of apical bud inhibits growth of the axillary (lateral) buds. Removal of the apical bud; B. A longitudinal section of the apical bud. Note shoot apical meristem with young leaf primordia promotes the growth of lateral buds into branches (C).

lated from the culture of the fungus. The western scientists, however, came to learn of the existence of gibberellins only after World War II. Presently, more than 100 different gibberellins have been identified, many of them occurring naturally in plants. Of these, gibberellic acid or gibbe-

rellin A, is the most thoroughly studied compound.

**Function of Gibberellins:** The major sites of gibberellin production in plants are embryos, roots and young leaves near the shoot tip. Gibberellins stimulate stem

elongation and leaf expansion, but have no effect on roots. The most striking effect of gibberellins is the elongation of genetic dwarf (mutants) varieties of plants such as corn and pea. Application of gibberellins to normal plants does not induce marked elongation. It is believed that certain types of dwarfness are due to gibberellin deficiency.

Another specific example of the action of gibberellins is in inducing stem elongation in 'rossette' plants. Cabbage is a good example of such a plant in which leaf development is profuse, whereas internodal growth is retarded. Just prior to the reproductive phase, the internodes elongate enormously causing a marked increase in stem height. This is called bolting. Bolting requires either long days or cold nights. If a cabbage head is kept under warm nights, it retains its rossette habit. Bolting in cabbage can be induced artificially by the application of gibberellins under conditions that would normally maintain the rossette form (Fig. 31.7).

Many seeds have high concentrations of gibberellins. At the onset of germination, gibberellins stimulate the production of digestive enzymes such as proteases, amylases, lipases, which help to mobilise stored nutrients. Even before these enzymes appear the hormone stimulates the production of messenger-RNA. Besides being involved in the breaking of seed dormancy and triggering germination, gibberellins function in breaking the bud dormancy. In this gibberellins act antagonistically to another hormone, ABSCISIC ACID.

Gibberellins, along with auxin, control fruit growth and development. Gibberellins cause parthenocarp in pome fruits (apple, pear) and are now used



**Fig. 31.7** Bolting in cabbage induced by gibberellin application. On the left are two control plants. The three plants on the right received a weekly dose of 0.1 mg gibberellic acid. Note the enormous elongation of the stem and flowering (Photo : Professor S. H. Wittwer, Michigan State University, East Lansing Michigan, U. S. A).



in India to increase the fruit size and bunch length in grapes. Gibberellins control flowering in LONG-DAY PLANTS and SEX EXPRESSION in certain species. In general, gibberellins promote the production of male flowers (either in place of female flowers in monoecious plants such as cucurbits or in genetically female plants such as *Cannabis*).

### Cytokinins

The discovery of cytokinins is an offshoot of the efforts of scientists to find chemical substances that would enhance the growth of mature plant cells and tissues in culture. Two substances were found to be effective—coconut milk and degraded samples of yeast DNA. The active ingredient in both of these turned out to be a modified form of adenine (one of the bases in nucleic acids). The substance was called KINETIN (6-furfurylaminopurine) because it promoted cell division (cytokinesis). The group of compounds thus came to be called cytokinins. They are produced in actively growing tissues such as embryos, developing fruits and roots.

This group of hormones almost never acts alone. In conjunction with auxins, cytokinins stimulate cell division even in non-meristematic tissues. In tissue cultures of parenchyma, mitoses are accelerated when both auxin and cytokinin are present; no response occurs with auxin or cytokinin alone. Furthermore, the ratio of cytokinins to auxins controls cell differentiation. When both are present in relatively equal quantities, cells divide but do not differentiate. If there is more cytokinin than auxin, shoot buds develop from a callus (derived from tobacco pith). If there is relatively more auxin than cytokinins, roots develop. Thus the pro-

portion of these two hormones controls organ formation in callus tissues. Interestingly these two hormones act antagonistically in the control of apical dominance. Auxin stimulates the growth of apical bud and cytokinins promote the growth of lateral buds.

Cytokinins can retard ageing of plant organs by controlling protein synthesis and mobilisation of resources. Cut leaves dipped in cytokinins stay green longer than the control leaves. Cytokinins induce flowering in certain species and also break the dormancy of some seeds.

### Ethylene (Gaseous plant growth regulator)

You must be familiar with the saying that a ripe or injured fruit in a basket hastens the ripening of other fruits. Kerosene lamps and hay have been used by merchants to hasten colour development in fruits. It is only recently that scientists have learnt that these effects are due to ethylene. Ethylene is unique in being the only gaseous natural plant growth regulator. Some of the inhibitory effects earlier attributed to auxin, are now known to be caused by ethylene. High concentrations of auxin induce ethylene formation. It is probable that this mechanism operates in the inhibition of root growth and development of axillary buds.

Ethylene modifies growth by inhibiting stem elongation and stimulating transverse expansion so that the stem looks swollen. Ethylene accelerates abscission of leaves, flowers, and fruits. It is also responsible for the changes that take place during fruit ripening. Ethylene is associated with the process of ageing of plant organs and triggering the ripening of fruits such as banana and citrus. Ethylene application increases the number of female flowers and fruits in cucumber plants.

## Abscissic Acid Growth inhibitors

Auxins, gibberellins and cytokinins are usually termed 'growth promoters'. Physiologists were aware that plant growth required promotion as well as inhibition. They were looking for control mechanisms that would cause retardation of growth during extremely cold or dry seasons. In the quest for naturally occurring substances that were responsible for bud dormancy and leaf abscission, plant physiologists discovered a growth regulator in the mid 1960's and called it ABSCISSIC ACID (ABA). ABA is of widespread occurrence in plants and usually interacts with other growth regulators. It inhibits mitoses in vascular cambium and causes active axillary buds to become dormant with the approach of winter. ABA is also involved in the dormancy of seeds. Dormant seeds germinate when ABA is overcome by gibberellins. ABA application to leaf causes the treated areas to become yellow—an effect opposite to that of cytokinin.

ABA also acts as a 'stress hormone', helping the plant to cope with adverse environmental conditions. For example, under severe drought, ABA prevents water loss by causing stomatal closure.

### **Interactions among Growth Regulators**

From the above account it is inferred that phytohormones do not act singly. All developmental processes in plants are regulated by phytohormones acting synergistically or antagonistically. As already explained, interactions between auxins and cytokinins control differentiation of organs in callus cultures. ABA and gibberellins regulate bud dormancy, cambial activity and seed germination.

### **Control of Plant Development**

In the life of most plants three distinct

phases may be recognised : (i) seed germination and vegetative growth phase, (ii) reproductive phase (flowering), and (iii) senescence and death. We shall now examine how the three phases of plant development are controlled.

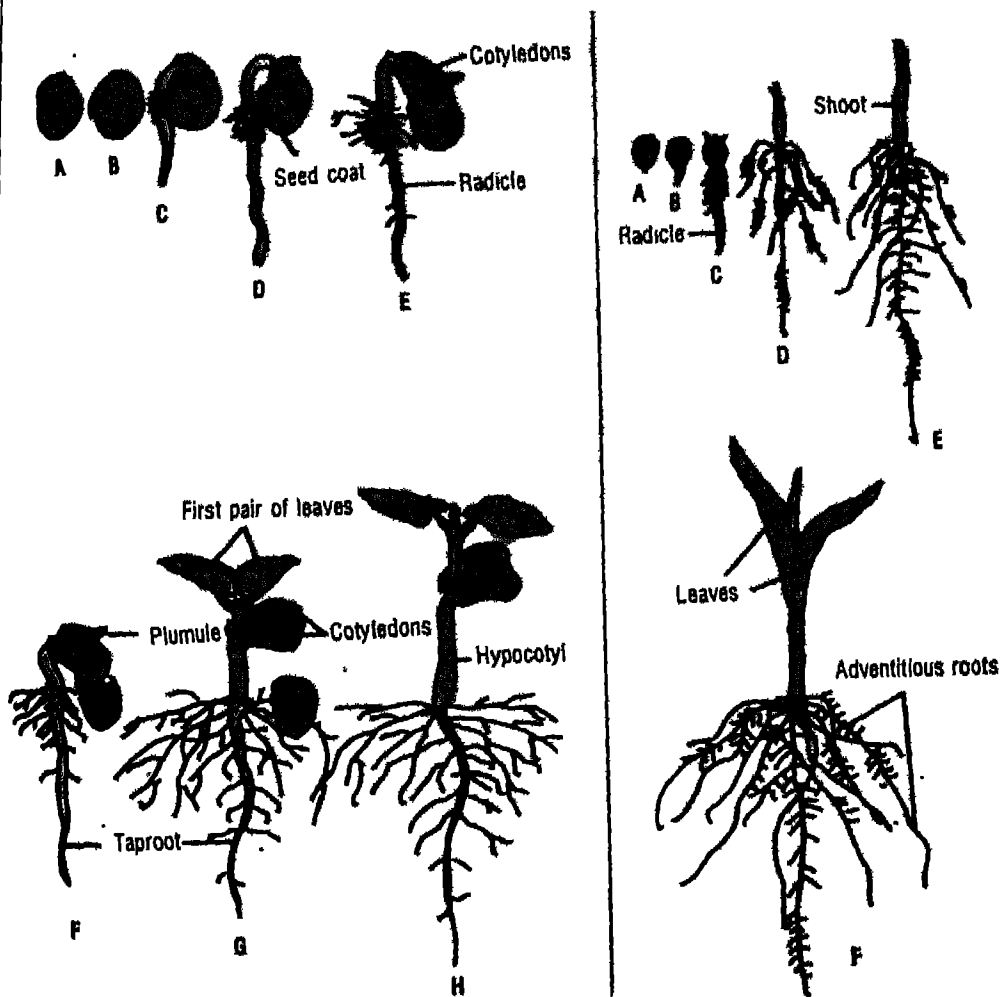
### **Seed Germination and Vegetative Growth**

You have studied in the last chapter that the sexually produced embryo develops within the seed. A significant feature of embryonal development in plants is that it stops growth and becomes dormant. Along with the dormancy of the embryo, the seed begins to lose its water content. Metabolic activities come to a virtual standstill as the seed coat becomes increasingly impermeable to oxygen and moisture. The embryo is now in a state of suspended animation. It is alive but hardly shows any signs of it. This is usually the stage when the seed (grain in cereals) is separated from the parent plant and is dispersed. The separated seed often lies in the ground and appears to wait for favourable cues (signals) and inputs from the environment to burst into life again. Obtaining these necessary conditions, the dormant embryo resumes metabolic activities and growth, a process we call seed germination.

**Conditions for Seed Germination:** Most seeds germinate on providing them with water and oxygen, the inputs which were withheld during seed formation and establishment of dormancy. However, in some seeds, dormancy may be broken only with additional signals from the environment. Though germination occurs over a wide range of temperature (5-40°C), the optimum is often around 25-30°C.

The first step in germination is IMBIBITION or uptake of water by the dehydrated

During germination in lima bean, the seed coat splits and the radicle comes out first and establishes a tap root. The hypocotyl forms a loop which subsequently straightens out to lift the cotyledons above the soil. The food stored in the cotyledons is used up and the plumule grows into a shoot. In maize, the single cotyledon never leaves the germinating grain. The plumule grows out of the coleoptile, pushing the soil. The radicle grows down, penetrating the coleorhiza. New roots arise from the axis to form the adventitious root system.



Seed germination in lima bean (left) and maize (right)

Viable <sup>seed</sup> = seed.

seed. Imbibition causes the seed to swell as the cellular constituents are rehydrated. It takes place with great force. It ruptures the seed coat and enables the radicle to emerge, (See Box for details of the process of seed germination in bean and maize.) Imbibition is due to rehydration of structural and storage macromolecules, chiefly the cell wall and storage polysaccharides and proteins. Many seeds have additional polysaccharides not commonly found in vegetative tissues. Imbibition can take place against great compressive force. Seeds packed dry in a bottle can crack it as they imbibe water and swell.

Imbibition of water causes resumption of metabolic activity. Initially metabolism may be anaerobic (due to the energy provided by glycolysis) but it soon becomes aerobic as oxygen starts entering the seed. The seeds of water plants, as also rice, can germinate under water by utilising dissolved oxygen. The seeds of plants adapted to life on land cannot germinate under water as they require more oxygen. It is for this reason that most seeds are planted in loose soil near the surface.

*Breaking of Dormancy in Seeds:* Seeds may not germinate either because they are not **VIALE**, that is dead, or because of continued dormancy even if proper conditions for germination are provided. You have already learnt in Chapter 30 about the causes of seed dormancy and the methods of breaking dormancy.

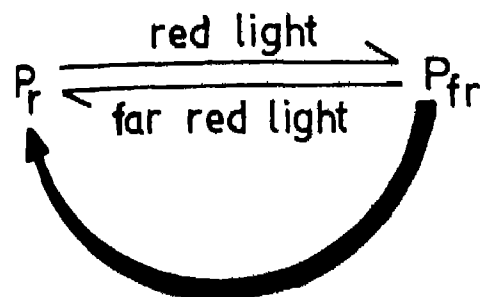
In some plants, light plays an important role in germination. Certain varieties of lettuce and tobacco do not germinate in darkness but quickly do so when exposed to light even briefly. In these light-sensitive seeds, the red region of the visi-

ble spectrum is most effective for germination. The far-red region (the region immediately after the visible red region) reverses the effect of red light and makes the seed dormant. The red and far-red sensitivity of the seeds is due to the presence of a proteinaceous pigment called **PHYTOCHROME**. Phytochrome is a regulatory pigment which controls several light-dependent developmental processes in plants besides germination in light-sensitive seeds. These include photomorphogenesis and flowering in a variety of plants.

*Phytochrome and Reversible Red—Far-red Control of Germination:* When brief exposures of red (R: 660 nm) and far-red (FR: 730 nm) wavelengths of light are given to soaked, light-sensitive lettuce seeds in close succession, the nature of the light provided in the last exposure determines the response of seeds. Germination occurs if it is red light (R) and germination is inhibited if it is far-red (FR) as shown below:

R .....	germination
R + FR .....	no germination
R + FR + R .....	germination
R + FR + R + FR ...	no germination

The pigment phytochrome that absorbs these wavelengths of light exists in two interconvertible forms, the red absorbing or  $P_r$  form and the far-red absorbing or  $P_{fr}$  form. On absorbing red light  $P_r$  becomes  $P_{fr}$ .  $P_{fr}$  becomes  $P_r$  either rapidly by absorbing far-red light or slowly in darkness. Germination and also other phytochrome-controlled processes are promoted by  $P_{fr}$ . Red light is needed to promote these. Darkness (or far-red) promotes  $P_r$  formation which induces dormancy and inhibits germination.



slow conversion in dark

Light requirement may be replaced by hormones such as gibberellins or cytokinins. Several developmental processes of plants controlled by phytochrome may be mimicked by appropriate hormones given singly or in combination at the correct time.

**Mobilisation of Reserves during Seed Germination:** During germination the cells of the embryo resume metabolic activity and undergo division and expansion. Stored starch, protein or fats have to be digested. These cellular conversions require energy provided by aerobic respiration.

Depending on the nature of the seed, the reserves may be chiefly in the endosperm (cereal grains, many monocotyledons and castor) or in the cotyledons (many dicotyledons such as peas and beans). The mobilisation of reserves from the endosperm to the embryo via a shield-like cotyledon has been thoroughly investigated in several cereal grains. The outer layer of special cells (ALEURONE LAYER) of the endosperm produces and secretes hydrolysing enzymes (such as amylase, proteases) which cause the breakdown of starch and proteins in the inner endosperm cells. Sugars and amino-acids so formed are transported to the embryo via

the cotyledon. Gibberellic acid plays an important role in initiating the synthesis of the hydrolysing enzymes. As explained earlier gibberellin therefore promotes germination and early seedling growth. Significantly, the dormancy-inducing hormone, ABA, prevents the germination-promoting action of gibberellin.

ABA has been shown to increase during the onset of dormancy of the embryo during seed development in several types of seeds. When young cotton embryos are removed and grown in culture, they continue to grow without any dormancy. Dormancy can be induced by adding ABA at a crucial stage of growth.

The developing seeds of some plants, such as mangroves, germinate within the fruit while still attached to the parent plant. This is called VIVIPARY. The mangrove plants therefore shed dart-like seedlings instead of seeds. These seedlings falling into the marsh immediately strike roots and establish themselves rather than get drifted away if shed as dormant seeds as during a high tide. The transition from the vegetative (juvenile) to the flowering (adult) stage may take several years in trees but only a few weeks or days in annuals. The onset of flowering has been a most fascinating subject of study.

### *Reproductive Phase (Flowering)*

That the reproductive phase has started in a plant can be recognised by the initiation of flower primordia in the apical and/or lateral shoot meristems. Often it is much later that flowers can be seen by the naked eye. Some species come to flower in a particular season, while others remain in the vegetative phase. Some other plants, such as tomato and cucumber, can bloom all through the year if temperature for their

growth is adequate. Naturally, many questions arise. How do plants which flower in a particular season, schedule their reproductive phase so precisely? What controls flowering?

You know that the daily and seasonal fluctuations in a particular location are directly related to latitude. For example, at the equator day length is of 12 hours duration all through the year, and the temperature is also fairly constant. In Singapore, for example, there is no marked variation in the average day length or maximum and minimum temperature. As one moves further from the equator, variation in day length and temperature during the various seasons of the year becomes more marked. Environmentally, the long warm days of summer are quite distinct from the short, cold days of winter. In the northern and southern latitudes plants take their cue for flowering from

the environmental conditions. The two main environmental factors that control flowering are day length or photoperiod (daily duration of light) and temperature.

**Photoperiodism:** Plants which respond to changes in the relative length of day and night are said to be photoperiodic. They exhibit the phenomenon of **PHOTOPERIODISM**.

In response to photoperiod the flowering response of angiosperms falls into three basic categories: (i) **SHORT-DAY PLANTS** initiate flowering when the day become shorter than a certain critical length. If these plants are kept in day lengths in excess of this critical point, they will remain vegetative. Common examples of short-day plants are cocklebur (*Xanthium*), Chrysanthemum, sugarcane, tobacco (mutant 'Maryland mammoth') and soybean. (ii) **LONG-DAY**

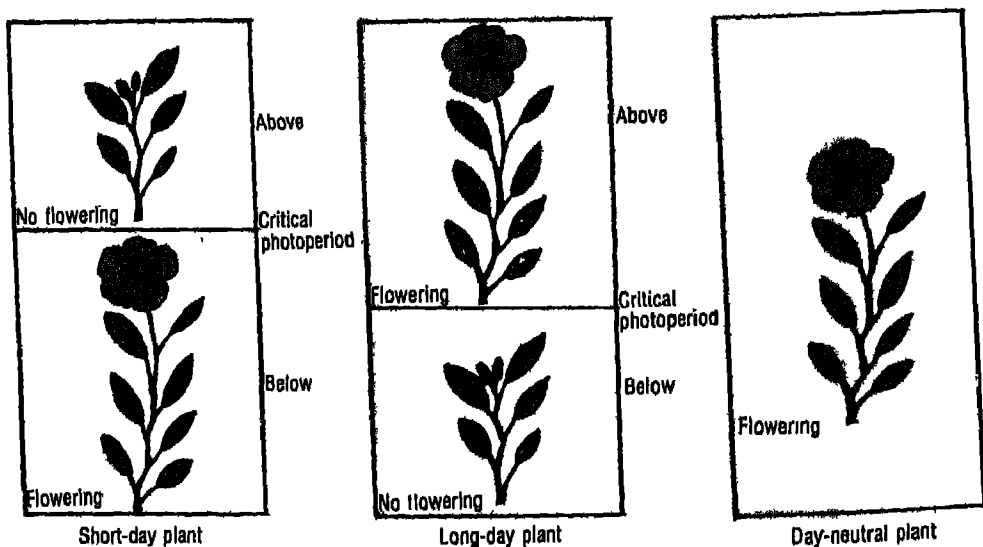


Fig. 31.8 Effect of day length on flowering

PLANTS begin flowering when the day length exceeds a critical length. Some common examples of long-day plants are spinach (*Spinacea oleracea*), radish, sugar-beet and henbane (*Hyoscyamus niger*). (iii) DAY NEUTRAL PLANTS flower after a period of vegetative growth, regardless of the photoperiod (Fig. 31.8). Some common examples of this category of plants are tomato, cucumber, cotton, sunflower, and some varieties of pea. The critical day length of both long-day and short-day plants tends to fall in the 12 to 14 hour range. Commercial flower-growers can induce or retard flowering by regulating the photoperiodic and temperature conditions in glasshouses to meet the demands of the market. The photoperiodic responses of plants are now known to be under the control of genes. These can be modified by various methods to yield varieties responding to required day lengths. For instance, scientists at the National Botanical Research Institute, Lucknow, have been able to breed varieties of *Chrysanthemum* which can bloom in different months of the year including summer.

The terms long-day and short-day plants are actually misnomers. When photoperiodism was discovered, the duration of the light period was thought to be critical for flowering. However, subsequently researchers found that when the long-night period was interrupted in short-day plants, by a brief exposure to light, they failed to flower (Fig. 31.9). In other words, the requirement is actually for a long night or a critical dark period rather than for a short day length. Similarly, long-day plants respond to nights shorter than the critical dark period. Curiously long-day plants do not need an uninterrupted dark night. Thus a short-day plant is more

appropriately called a long-night plant and a long-day plant as a short-night plant even though the earlier terminology continues to be used.

Physiologists were also curious to find out whether flowering depended on the quality of light. In the night interruption experiments, flowering was inhibited when the short-day plants were exposed to red light (660 nm). If this was followed by exposure to far-red light (740 nm) the effect was reversed. As with seed germination experiments, the R, FR exposures given in succession showed that in flowering also the last exposure determined the response (Fig. 31.9). Thus flowering is also a phytochrome-mediated process.

One important question that needs to be answered is : what part of the plant perceives the light stimulus ? It has been demonstrated that a plant from which all leaves have been removed fails to flower even under the inductive light regime. Further confirmation came from experiments with *Xanthium*, a short-day plant. Even if one-eighth of a leaf was exposed to short days, flowering occurred. Further, a single leaf exposed to short days was able to induce flowering when it was grafted on to a plant kept under non-inductive conditions.

These findings indicate that some sort of stimulus moves from the light-exposed leaves to the shoot to induce flowering. The floral stimulus is not species-specific because grafting an induced twig of *Xanthium* onto a vegetative soybean plant can cause the latter to flower.

The nature of the flower-producing stimulus has been widely debated. Some plant physiologists have proposed the existence of a flowering hormone- 'florigen'. Unfortunately, florigen has never been isolated. However, research

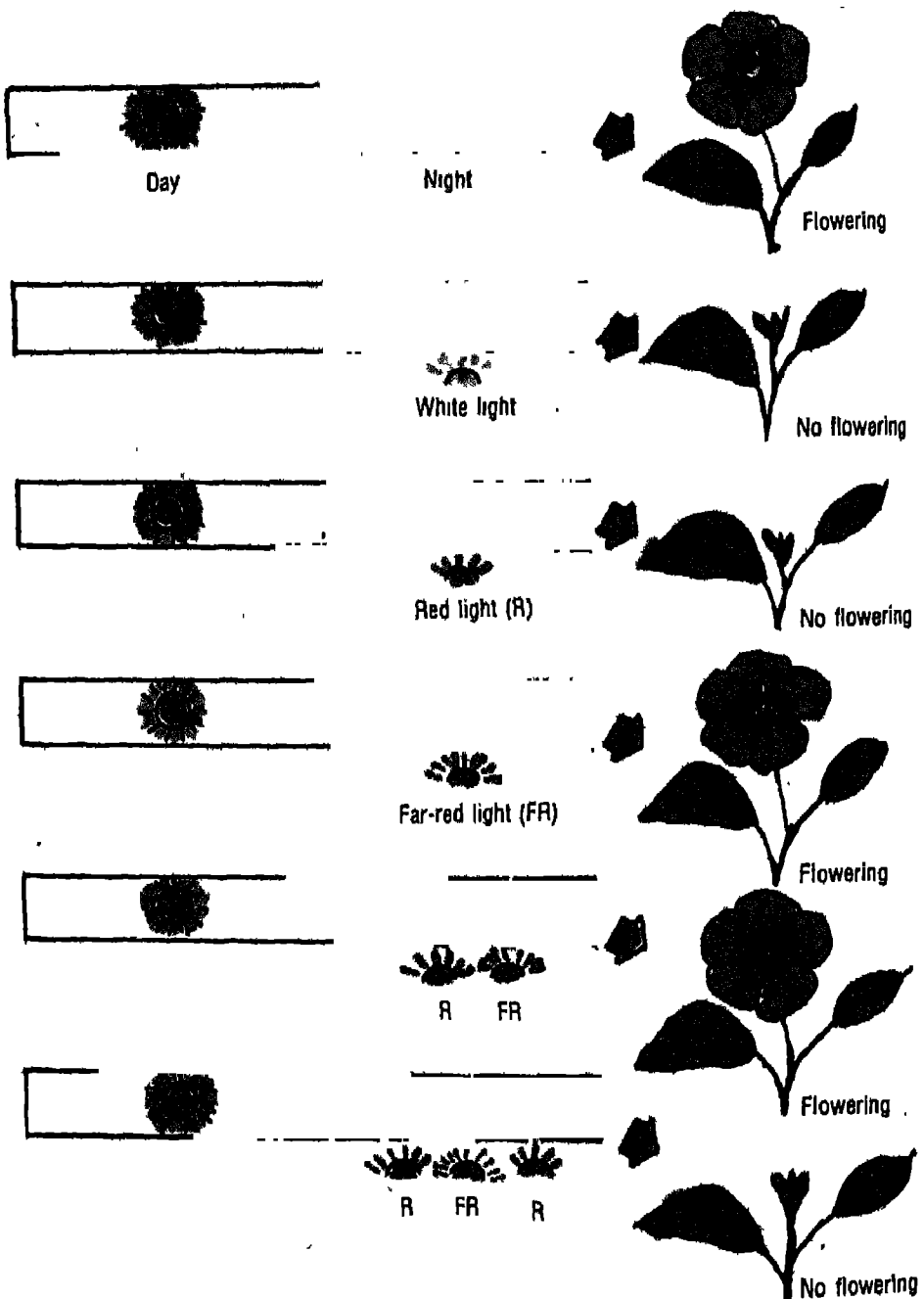


Fig. 31.9 Effect of night (dark) interruption on flowering in a short-day plant



has indicated that flowering is controlled by the interplay of auxins, gibberellins,

Vernalization was first studied in Europe on the winter varieties of cereals such as wheat, barley, oats and rye. When sown in spring, they failed to flower the same year but only grew vegetatively. Such winter varieties sown in the autumn of the preceding year flowered in spring the next year. By vernalization, such winter varieties could be made to flower the same year.

Vernalization treatment is given as follows : Seeds are moistened sufficiently to allow germination to begin. They are then exposed to a temperature of 0-4°C for a few weeks. When sown in the spring such vernalized seeds produce a crop in the summer of the same year. This technique was developed in the USSR to avoid killing of cereals in severe winters. The cold stimulus is perceived by the shoot apical meristem. Grafting a cold-treated twig onto an untreated plant brings about flowering in the latter, showing thereby the existence of a cold-induced stimulus, called VERNALIN. The chemical nature of vernalin is not known. However, gibberellins can substitute for cold treatment in certain species.

cytokinins and ethylene. Hormone application can substitute for the necessary photoperiod and can trigger floral development in certain plants.

Vernalization : Temperature has a profound effect on flowering. It has been

found that certain plants will flower only when they are exposed to low temperatures for a few or several weeks. This low temperature requirement for flowering is called VERNALIZATION. It is important to note that vernalization itself does not induce flowering. It prepares the plant to flower.

### *Senescence and Death*

The production of flowers, fruits and seeds in annuals and biennials leads to senescence. Senescence may be defined as the period between reproductive maturity and death of a plant or a plant part. During senescence the functional capacity decreases, cellular breakdown and metabolic failures increase. In rice, wheat, gram and mustard the whole plant dies after seed production. This is referred to as WHOLE PLANT SENESCENCE. Such a condition is observed even in monocarpic (living for several years but flowering once) plants such as certain bamboos and sago palm. In many other perennial plants, the tips of main shoot and branches remain in a meristematic state and continue to produce new buds and leaves. The older leaves and lateral organs senesce and die. This is called SEQUENTIAL SENESCENCE. In certain perennials such as banana and gladiolus, the above-ground part of the shoot dies each year after flowering and fruiting, but the underground part (stem and roots) survives and puts out new shoots again next year. This condition is termed SHOOT SENESCENCE. In temperate deciduous trees such as elm and maple all the leaves are shed in late autumn (October). This is SIMULTANEOUS or SYNCHRONOUS SENESCENCE (Fig. 31.10). Biologically senescence and death have manifold advantages. Old and inefficient organs are

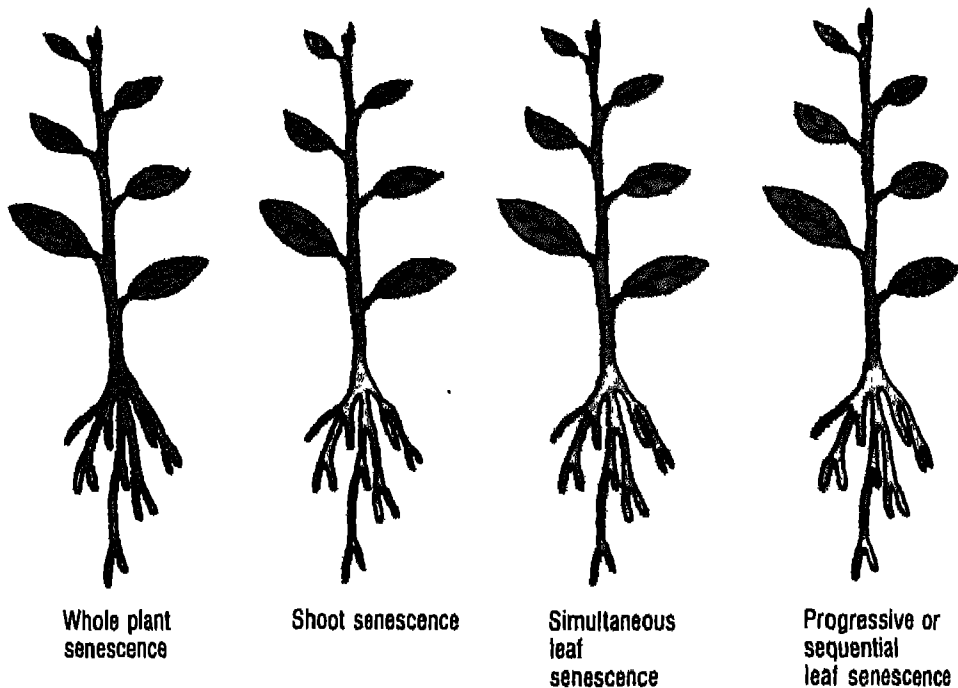


Fig. 31.10 Types of plant and leaf senescence

replaced by young and developing leaves, buds, flowers and fruits. In certain trees when the older organs are shed, nutrients are withdrawn into the main trunk and later diverted to the younger parts. Leaf fall reduces transpiration loss, which is essential for survival in winter when the soil is frozen and roots cannot absorb water. Further, leaf litter releases mineral nutrients to the soil which are available for reutilisation.

### Movements

Unlike animals, plants are anchored to a spot and do not move. They are subject to movement by forces of wind or water. But do plants move on their own? Yes, plants

are in continuous motion. It is so slow that it is difficult to see. Time-lapse cameras can capture the twining of a vine around a support or the stately dance of a coiling tendril. Movements of plant parts are generally classified as GROWTH MOVEMENTS and TURGOR MOVEMENTS.

Growth movements are due to differential (or unequal) growth. Cells in one part of the affected organ grow faster than in another part, thus changing its position. Turgor movements are due to differences in water potential of the affected organs and these are reversible under changed conditions. However, growth movements are less easily reversed. Some growth movements are self controlled (AUTO-

NOMIC), such as in NUTATION where the spatial twisting of the stem occurs as it grows. Others are induced by external stimuli (PARATONIC). The paratonic movements may be further classified into TROPIC MOVEMENTS which are responses to stimuli chiefly from one direction and NASTIC MOVEMENTS which are caused but not directed by external stimuli as will be explained below.

TROPISMS can be of various types depending on the nature of the external stimulus; for example GEOTROPISM or GRAVITOTROPISM (response to gravity), THIGMOTROPISM (response to touch), THERMOTROPISM (response to temperature), HYDROTROPISM (response to water), CHEMOTROPISM (response to chemicals) and PHOTOTROPISM (response to light). The most common of these is the bending of plants towards light which may be observed by keeping a potted plant near a window. Nastic movements are not directional like tropic movements. The opening of a flower with a change in light intensity is a PHOTONASTIC response. Sleep movements in many leguminous plants such as siris (*Albizia lebbek*) or rain tree (*Samanea saman*) are called NYCTINASTY.

Turgor movements result from differential changes in turgor of some cells. The rolling of leaves of many grasses in dry weather is caused by the loss of turgor and

collapse of large thin walled BULLIFORM CELLS on the surface. The movement in *Mimosa pudica* (touch-me-not) which is sensitive to touch, is also an example of turgor changes.

When a plant of *Mimosa* is touched its leaves collapse and leaflets fold together. It is one of the rare plant movements that can be easily seen. This occurs in a second or two because of the loss of turgor by cells within the PULVINI (specialised motor organs located at the joints of leaf). The motor cells suddenly become flaccid. After stimulation they lose  $K^+$  ions which causes water to leave the cells by osmosis. It takes about ten minutes for the cells to regain the turgor and the leaflets to open out.

A remarkable feature of the rapid leaf movements is the transmission of the stimulus through the plant. From the point of stimulus the message to respond travels in waves through the plant at a speed of about one centimetre per second. Certain chemical substances may play a role in transmission. Electrical impulses, called action potentials, just like the nervous messages in animals, have been detected in *Mimosa pudica*.

## SUMMARY

A seedling of a flowering plant represents only a fraction of the final condition attained by the adult. Plant growth represents an irreversible increase in size, weight, or volume. To sustain growth, the rate of anabolic processes must exceed that of catabolic processes. Active cell divisions occur in apical meristems (shoot and root) and

in lateral meristems (cambium, phelloderm, leaf bases etc.). As new cells are formed, the older cells enlarge, differentiate and come to occupy various positions in the plant body and take up specific functions.

When the growth of an annual plant or of a plant organ (e.g. leaf or fruit) is measured and plotted as a function of time, a sigmoid curve is obtained. It shows lag, exponential and stationary phases. Whereas the life-cycle of an annual is terminated by fruiting, growth in perennials is continuous. It is interrupted by periods of dormancy. In the trees of the temperate and sub-tropical regions, well-defined annual growth rings are observed in the wood as seasons are well-marked. In a flowering plant a period of vegetative phase (juvenile phase) precedes the reproductive phase (adult phase). These phases are controlled by internal and external factors.

Among the internal factors certain naturally occurring chemical substances, called growth regulators or phytohormones, are important. These include auxins, gibberellins, cytokinins, ethylene and abscisic acid.

Auxins cause cells elongation, cell division in vascular cambium, root initiation and callus formation. Auxins are also involved in apical dominance and abscission. Synthetic auxins are used as herbicides, rooting hormones and for prevention of pre-harvest fruit drop.

Gibberellins cause the elongation of stems of genetically dwarf plants. The major sites of gibberellin production are embryos, roots and young leaves. Gibberellins cause bolting of rosette plants and induce production of hydrolysing enzymes in germinating seeds. Gibberellins break bud dormancy, induce parthenocarp and substitute for long day requirement in long-day plants.

Cytokinins promote cell division even in non-meristematic tissues. In association with auxin, cytokinin controls cell differentiation and formation of shoot buds in callus tissues. Cytokinins are involved in the retardation of senescence, induction of flowering and breaking of seed dormancy. Ethylene is a gaseous hormone implicated in abscission of organs and acceleration of fruit ripening.

Abscisic acid (ABA) is a growth inhibitor. Prevention of cell division and dormancy of buds, tubers and seeds are attributed to ABA.

Plant growth results from promotion and inhibition, mediated by the interaction of phytohormones.

Plant development begins when the embryo in a dormant seed recommences its growth as the factors that impose dormancy are overcome by various types of influences. Availability of water and oxygen and a suitable temperature are important requirements. As dormant seeds imbibe water, their metabolic activities are initiated and reserve food materials are mobilised. In many seeds, germination is controlled by light. Red light stimulates germination and far-red light retards it. In such seeds germination is under the control of the pigment phytochrome which exists in two interconvertible forms  $p_r$  and  $p_{fr}$ . Light requirement for germination can be substituted by gibberellins or cytokinins. Abscisic acid induces dormancy and gibberellins break it.

Reproductive growth is characterised by the formation of flowers. The exact mechanism that initiates flowering in all plants is not known. However, in several plants flowering is under the control of daily length of light (photoperiod) and temperature. Short-day plants are those that flower when the day length is below a certain critical level. Long-day plants are those that flower when the day length exceeds the

critical day length. It is the dark period which is critical for flowering. The plants whose flowering is not affected by day length, are termed day-neutral.

Phytochrome plays an important role in flowering. Although some physiologists believe that a universal flowering hormone 'florigen' exists, it has not been isolated. The low temperature requirement for flowering is called vernalization.

In annuals, biennials and monocarpic plants, flowering and fruiting lead to whole plant senescence and death. Senescence involves gradual cessation of functional activity and cellular breakdown. In certain plants only the aerial shoot dies but the underground parts survive and put out fresh shoot (s). In perennials flowering and fruiting occur at definite seasons but they do not trigger ageing of the plant. Only leaves, flowers and fruits are shed periodically. Continuous replacement of organs maintains a plant's efficiency and helps in the recycling of nutrients.

Flowering plants show growth movements and turgor movements. Growth movements are so slow that they can be observed through time-lapse photography. Some growth movements are self-controlled e.g. nutation. Others are induced by external stimuli such as light, gravity or contact. Turgor movements are due to differences in water potential in different parts of the plant.

## QUESTIONS

1. Explain the biological meaning of growth. In what essential ways does plant growth differ from animal growth?
2. Tick (✓) the correct answers in each of the following:
  - (a) The maximum growth rate occurs in
    - (i) exponential phase
    - (ii) lag phase
    - (iii) stationary phase
    - (iv) senescent phase
  - (b) The hypothetical 'florigen' could be released prematurely in a long-day plant by exposing it to
    - (i) far-red light during the day
    - (ii) far-red light during the night
    - (iii) red light during the day
    - (iv) red light during the night
  - (c) Mobilisation of stored food in germinating seeds is triggered by
    - (i) auxins
    - (ii) cytokinins
    - (iii) gibberellins
    - (iv) ethylene
3. Discuss the role of interaction among phytohormones in the development of plants, giving suitable examples.
4. Explain how the method of science operated in the discovery of auxins.
5. Explain the role played by phytochrome in seed germination.
6. Explain how it is possible that a short-day plant and a long-day plant growing in the same location could flower on the same day of the year.

7. Distinguish between
  - (a) Tropic and nastic movements
  - (b) Phototropism and photoperiodism
  - (c) Long-day and short-day plants
8. (a) Why is the term long-day plant a misnomer ?  
(b) What is the difference between 'florigen' and other growth hormones ?
9. Define senescence. What are the various types of senescence observed in plants?  
Can senescence be retarded by growth regulators.?
10. Discuss the role of growth regulators in agriculture.

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## UNIT SIX

### *Multicellularity in Animals*

THE multicellular animal body is made up of many cells of diverse types. These cells show a wide range of structural and functional specialisations. Still, all of them retain remarkable similarities in their basic structures and fundamental cellular process. A considerable division of labour evolves among the cells of a multicellular animal and improves the performances of the organism. Specific types of cells, joined by intervening extracellular materials, constitute a tissue. Each tissue serves specific functions, some covering surfaces and secreting juices, some conducting information, some bringing about movements of body parts and locomotion, and some joining different tissues with each other. Functions of a tissue emerge from the cooperation and coordination between its cells. Several types of tissues are set together in an organ with specific functions. Several organs are in turn organised into an organ-system entrusted with some major biological activities. A coordination between the organ-systems maintains the life of the organism.

Animals acquire energy in the form of food materials. The digestive system carries out the hydrolysis of large complex organic molecules of food into simpler and smaller molecules and absorbs them into the body. These small molecules are subsequently used either in generating energy through oxidation or in building up large complex molecules characteristic of the particular species. Carbohydrates and fats are mainly used as fuel for producing energy. Proteins are mainly utilised in forming structural, carrier and catalytic molecules in the body. Vitamins and minerals mainly help in various chemical reactions as coenzymes or cofactors. Some of the minerals like calcium and phosphorus enter into structural components of the body also. Deficiencies of these nutrients produce various malnutritional diseases.

To oxidise the food molecules for energy production, the animal has to take in oxygen from the surrounding environment. It has also got to eliminate the carbon dioxide produced by such oxidation. The respiratory system carries out the exchange of these respiratory gases between the animal and the environment.

Nutrients, respiratory gases and hormones have to be distributed to the organs and tissues in different parts of the body. Waste products have also to be carried from different tissues to the organs of the excretion. All these are transported in the blood which is circulated throughout the body by the circulatory system. The excretory system removes the waste products from the blood and eliminates them from the body to maintain the constancy of the internal environment of the body.

To remain alive, the animal must get acquainted with the changes occurring inside and outside its body. It must also respond suitably to such changes. For these purposes, information has to be transmitted between different parts of the body. This is done in two ways. The nervous system conducts the information in the form of propagated electrical potentials called nerve impulses. The endocrine system secretes a number of hormones which are carried by blood to different tissues and organs. Nerve impulses and hormones regulate the activities of tissues and organs to control body activities.

The skeletal system supports the weight of the body and protects the internal organs. The muscular system carries out movements of organs as well as locomotion of the animal. The reproductive system is entrusted with the responsibility of continuing the species through reproduction.

With the evolution of multicellularity, cells have increased both in number and in diversity in the animal body. Division of labour between the cells requires them to function in a well-concerted and integrated manner. Functions of each organ depend on the cooperative and collective actions of many cells of diverse types. Functions of each system result in turn from the coordinated activities of more than one organ. Life is maintained by the coordination and cooperation between all the organ-systems. In spite of their diversities, all cells of the multicellular body have to function with a considerable degree of unity among themselves.

The story of animal development is a fascinating one. The multicellular animal begins its life as a single cell—the fertilised egg. To attain specific organisation, it passes through a series of dynamic changes. Three basic events of these changes are cell multiplication, movement of cells, growth and tissue differentiation leading to the emergence of the characteristic form and structures. With the development of organs and organ-systems, the animal attains the functional state as an individual. Interestingly, the developmental changes continue throughout life of the individual in the forms of growth, repair, regeneration and finally ageing.

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**ANIMAL TISSUES**

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THE single cell of a unicellular organism performs all life activities. Many cells share the biological activities of a multicellular organism. Cells of multicellular organisms undergo differentiation and each type of cells is specialised for a limited number of specific functions. In the multicellular organism, cells coordinate their activities, support one another, exchange nutrients, metabolites and provide information. They influence and modify each other's performance and even replace dead or lost cells. The existence of a multicellular organism depends on such cooperative and integrated activities of all the constituent cells, even though they maintain their individuality for many basic biological processes.

**Organisation of Tissues, Organs and Organ-Systems**

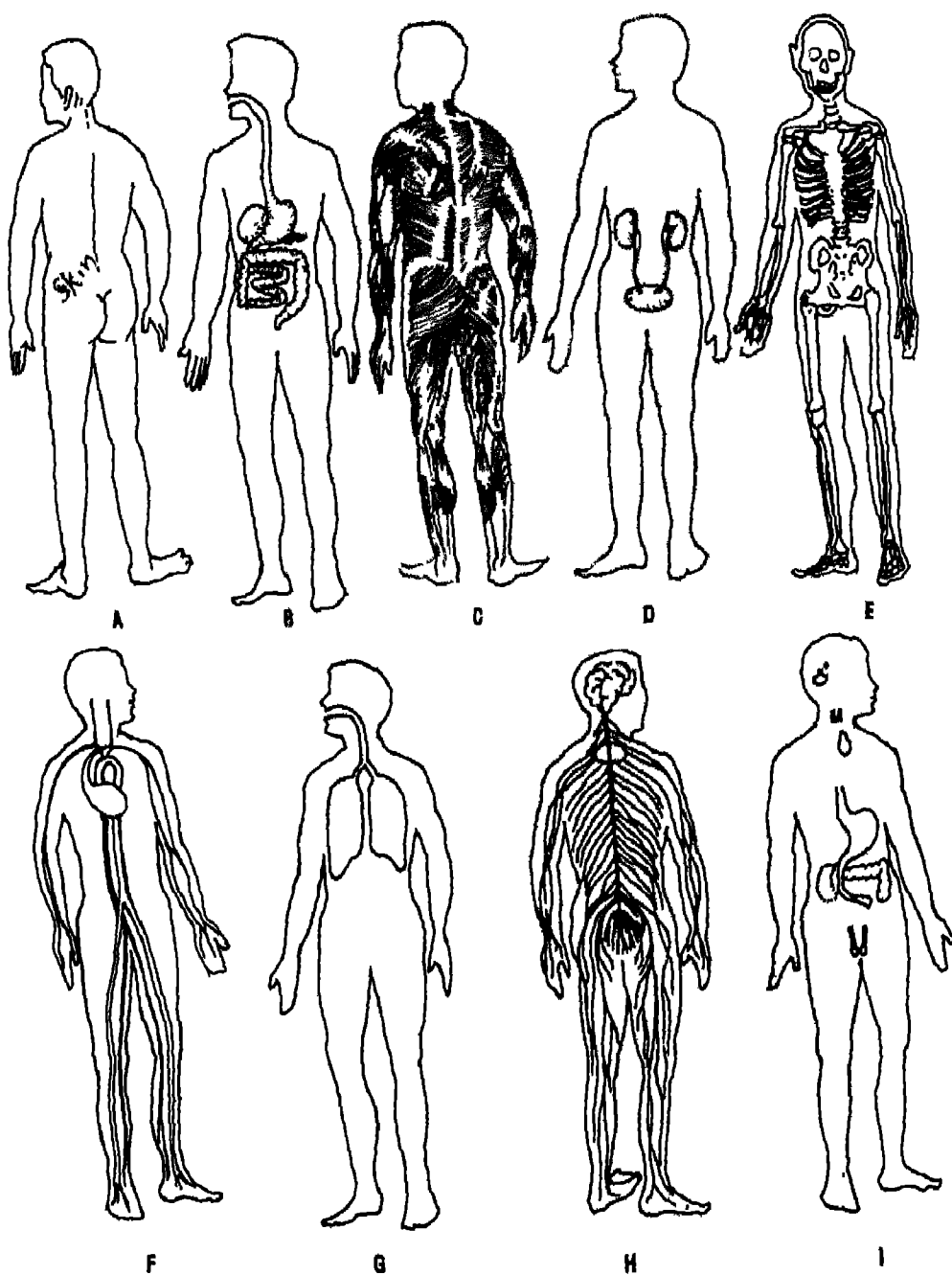
With specialisation and differentiation, cells develop a considerable degree of division of labour among themselves in the multicellular animal body. This improves their performance. Cells also

form **EXTRACELLULAR** or **INTERCELLULAR MATERIALS**. These materials surround the individual cells, separate them from each other and bind them together. One or more types of specialised cells are set in specific extracellular materials to constitute a tissue.

The nature and amount of extracellular material vary from tissue to tissue. In some tissues, the extracellular material is limited to very thin layers, just separating the cells and barely visible under the light microscope. In some other tissues, the extracellular material is quite vast in proportion to cells and separates them widely apart from one another.

Cells of a tissue, when not separated widely by extracellular materials, are often held together by structures called **CELL JUNCTIONS**.

Animal tissues are divided into four major classes on the basis of their functions. EPITHELIAL TISSUE covers free surfaces of other tissues. CONNECTIVE TISSUE joins, supports and holds other tissues together. MUSCLE TISSUE causes the move-



**Fig. 32.1** Nine organ-systems of human body (diagrammatic)

A. Integumentary system; B. Alimentary system; C. Muscular system; D. Excretory system; E. Skeletal system; F. Circulatory system; G. Respiratory system; H. Nervous system and I. Endocrine system

ment of the skeleton and the internal organs by contraction. NERVE TISSUE transmits messages in the form of impulses.

An ORGAN as for example, stomach, liver, pancreas or urinary bladder, is made up of different types of tissue. Each organ performs specific functions, which depend on the collective and integrated activities of its tissues.

Several organs constitute an ORGAN-SYSTEM (Fig. 32.1). Organs of a system function in a coordinated manner to carry out a major life process. For example, kidneys form urine, ureters conduct it to the urinary bladder, and the latter stores it and periodically expels it through the urethra. Thus these organs of the EXCRETORY SYSTEM are involved in the elimination of

waste products. The DIGESTIVE SYSTEM carries out digestion and absorption of food. The RESPIRATORY SYSTEM is entrusted with the job of exchanging of gases between the organism and its environment. The CIRCULATORY SYSTEM is responsible for the transport of nutrients, respiratory gases, metabolites, hormones and waste products between different parts of the body. The ENDOCRINE SYSTEM consists of glands which secrete hormones for regulating the functions of other organs and tissues. The NERVOUS SYSTEM receives information of external and internal changes to give rise to sensations, transmits information among different parts of the body in the form of propagated potential changes, and regulates other systems. The REPRODUCTIVE SYS-

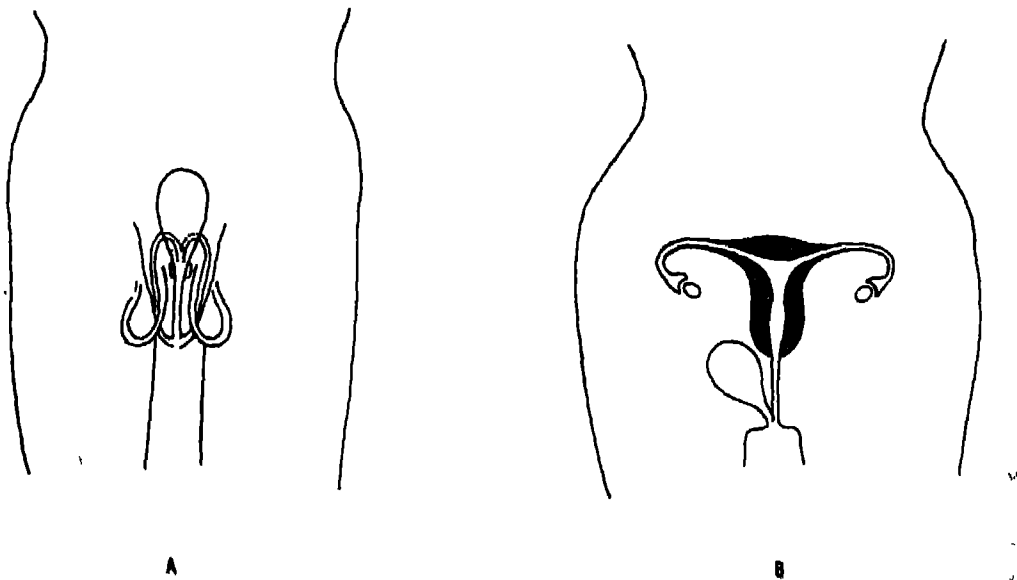


Fig.32.2 Human reproductive system : A. in male and B. in female (diagrammatic)

Table 32.1

## ORGANS OF MAMMALIAN ORGAN-SYSTEMS

1. Digestive System	3. Circulatory System	6. Reproductive System
Mouth	Heart	(a) Male:
Tongue	Arteries	Testes
Salivary glands	Arterioles	Epididymis
Pharynx	Capillaries	Vas deferens
Oesophagus	Venules	Seminal vesicles
Stomach	Veins	Prostate
Small intestine	4. Excretory System	Cowper's glands
Large intestine	Kidneys	Penis
Liver	Ureters	(b) Female:
Gall bladder	Urinary bladder	Ovaries
Bile ducts	Urethra	Fallopian tubes
Pancreas		Uterus
	5. Endocrine System	Vagina
2. Respiratory System		Mammary glands
Nostrils	Pituitary	
Nasal passages	Thyroid	7. Nervous System
Nasopharynx	Parathyroids	Brain
Larynx	Adrenals	Spinal cord
Trachea	Pancreas (islets)	Lateral sympathetic chains
Bronchi	Pineal	Peripheral ganglia and nerves
Bronchioles	Thymus	Eyes
Lungs	Testes	Ears etc.
	Placenta	
	Ovaries	

TEM is responsible for the multiplication of organisms (Fig. 32.2). The SKELETAL SYSTEM supports the body and protects the softer internal organs from external injury. The MUSCULAR SYSTEM participates in movements and locomotion. Thus, the life of an organism is maintained by the cooperative activities of its organ-systems.

The major organs of some of the sys-

tems of mammals are listed in Table 32.1. Their functions will be discussed in the subsequent chapters.

## ANIMAL TISSUES

## Epithelial Tissues

The epithelial tissue forms a continuous layer over the free surfaces of many other tissues. Consequently, it covers the exter-

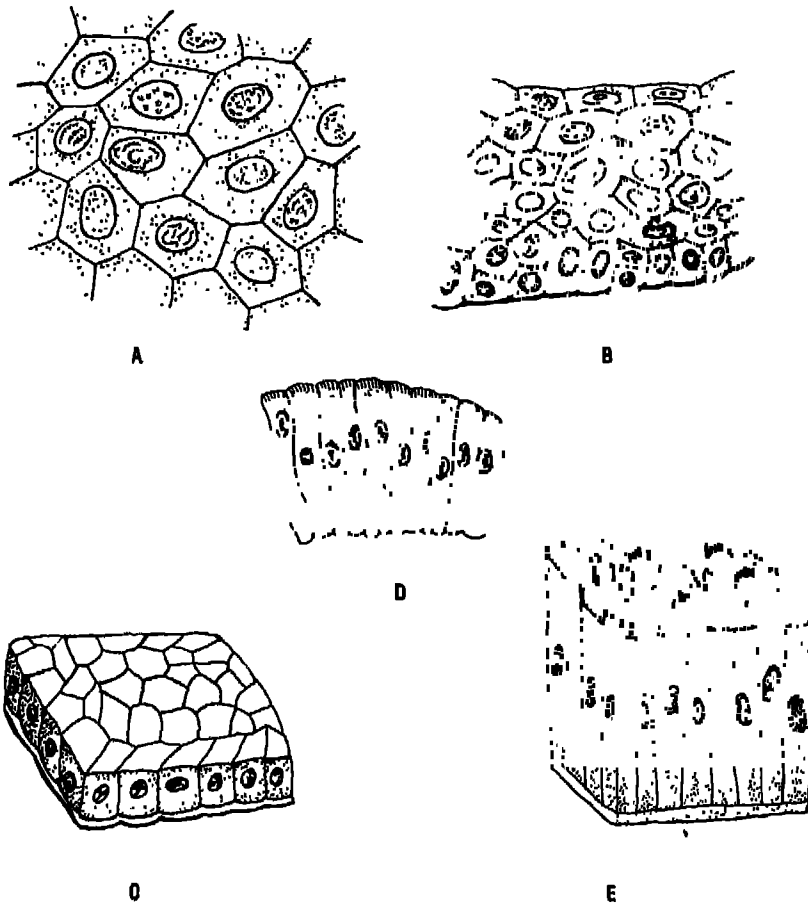


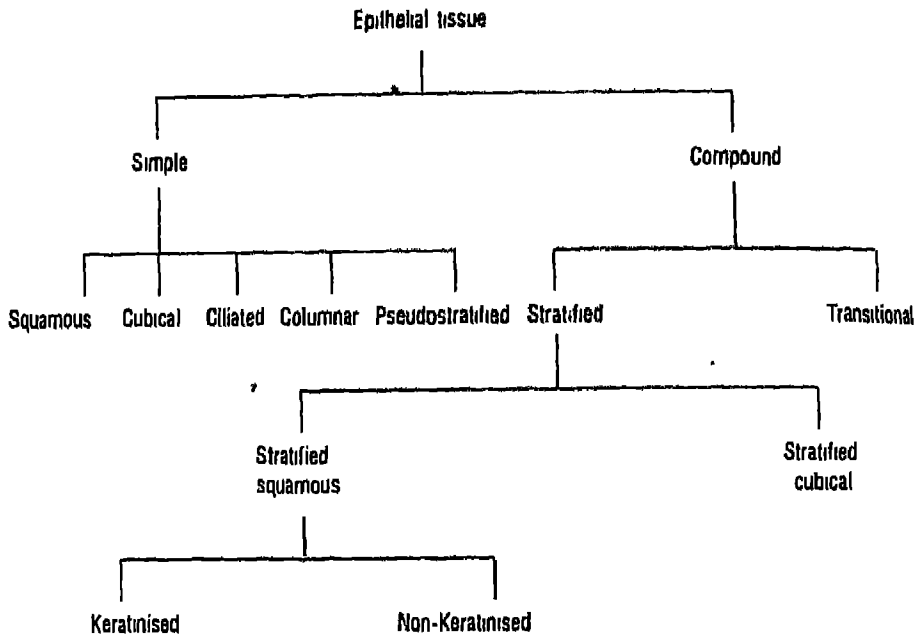
Fig. 32.3 Different types of epithelial tissues

A. Squamous; B Stratified squamous; C. Cuboidal; D. Columnar and E. Ciliated columnar

nal surface of the animal body and the internal (luminal) surfaces of visceral organs, body cavities and blood vessels. It protects the underlying or overlying tissues. Materials are exchanged at the surfaces across the epithelial tissues.

Cells of the epithelium are set very close to each other, separated by very thin films of extracellular material. Neighbouring cells are held together by cell junctions. The epithelial tissue rests on a noncellular BASEMENT MEMBRANE, which separates it

**Table 32.2**  
**CLASSIFICATION OF EPITHELIAL TISSUES**



from the underlying connective tissue.

Linings of some hollow organs or cavities are moist because of mucus secreted by the epithelial tissue. Such a lining consisting of the epithelium and the supporting connective tissue underneath is called a MUCOUS MEMBRANE or MUCOSA.

Blood vessels are absent in the epithelial tissue. Materials are exchanged between epithelial cells and vessels of the connective tissues by diffusion across the basement membrane. The epithelial tissue (Fig. 32.3) is classified into simple and compound epithelia (Table 32.2).

#### Simple Epithelium

It is formed of a single layer of cells, resting on the basement membrane. Simple epithelium occurs mainly on secretory and absorptive surfaces. It seldom covers

surfaces exposed to mechanical or chemical abrasions because it is not effective in protecting the underlying tissues.

SQUAMOUS EPITHELIUM consists of a layer of thin, flat, scale-like cells with prominent nuclei (Fig. 32.3). The cells have irregular boundaries that fit closely into those of neighbouring cells. It forms the inner lining of lung alveoli and blood vessels, oesophagus.

CUBICAL EPITHELIUM (Fig. 32.3) has cells which are polygonal in outline, but appear cuboidal in vertical section. It lines small salivary and pancreatic ducts and thyroid vesicles. The cells participate in secretion, excretion and absorption. The cells of cubical epithelium in absorptive surfaces often bear MICROVILLI on their free ends. This gives a brush-like appearance to their free border. They are,



therefore, called BRUSH-BORDERED CUBICAL EPITHELIAL CELLS, e.g. in proximal tubules of kidneys. Microvilli greatly increase the area of the free surface of the cell and thereby enhance absorption.

COLUMNAR EPITHELIUM is characterised by the presence of tall cells shaped like polygonal columns (Fig. 32.3). The nucleus is usually located at the base of the cell. Columnar epithelium covers the inner surface of the intestine, stomach and gall bladder. It also occurs in gastric and intestinal glands. Its function is secretion or absorption. The intestinal mucosa is lined by BRUSH-BORDERED COLUMNAR EPITHELIUM which is highly absorptive.

CILIATED EPITHELIUM consists of columnar or cubical cells bearing CILIA on their free surfaces (Fig. 32.3). The function of the cilia is to move particles, free cells or mucus in a specific direction over the epithelial surface. Ciliated epithelium lines the inner surfaces of some hollow organs such as Fallopian tubes, bronchioles and small bronchi.

PSEUDOSTRATIFIED EPITHELIUM covers the inner linings of trachea and large bronchi. Although made up of a single layer of columnar cells, it appears two-layered, because some cells are shorter than the others and have their nuclei at a different level. The shorter cells lack cilia and secrete mucus which traps particles on the epithelial surface. The longer cells are ciliated. The ciliary movement propels the mucus and the particles towards the larynx.

### Compound Epithelium

It consists of more than one layer of cells. Only the cells of the deepest layer rest on the basement membrane. Being multilayered, compound epithelia have little role in secretion or absorption; but

they provide protection to underlying tissues against mechanical, chemical, thermal or osmotic stresses. Compound epithelia may be stratified or transitional.

STRATIFIED EPITHELIUM has many layers of epithelial cells. The deepest layer is formed by cuboidal cells. But the morphology of the superficial layers varies in the different kinds of stratified epithelia. In STRATIFIED CUBOIDAL EPITHELIUM the superficial cells are cuboidal. It lines the inner surfaces of larger salivary and pancreatic ducts. STRATIFIED SQUAMOUS EPITHELIUM (Fig. 32.3) covers moist surfaces such as those of buccal cavity, pharynx and oesophagus. It has several superficial layers of living squamous cells and deeper layers of interlinked polygonal cells. STRATIFIED KERATINISED SQUAMOUS EPITHELIUM covers the dry surface of skin. It has many superficial layers of horny, scale-like remains of dead squamous cells and several deeper layers of living polygonal cells. Heavy deposits of the insoluble protein keratin in the dead superficial cells make the epithelium impervious to water and highly resistant to mechanical abrasions. In contrast, non-keratinised stratified epithelia cannot prevent water loss and afford only moderate protection against abrasions.

TRANSITIONAL EPITHELIUM is much thinner and more stretchable than the stratified epithelium. It has a single layer of cuboidal cells at the base, 2-3 middle layers of large polygonal or pear-shaped cells and a superficial layer of large, broad, rectangular or oval cells. It lines the inner surface of the urinary bladder and ureters. It prevents loss of water from blood to urine. It also allows considerable expansion of these organs to accommodate urine, because stretching considerably

**Activity 1:** Scrape the mucous membrane on the inner surface of your lower lip with the edge of a sterilised spatula or coverslip. Place the scrapings on a glass slide, add a drop of 0.9% NaCl solution (this concentration is isotonic to the mammalian tissue fluid) and place a coverslip over it. Put a drop of 1% methylene blue solution on the edge of the coverslip. The dye runs under the coverslip and stains the scrapings. Wipe off the excess dye with a blotting paper without disturbing the coverslip. Examine the preparation under the low and high power objectives of a microscope. You will see irregularly polygonal, scale-like squamous epithelial cells, each with a centrally placed nucleus stained blue.

**Activity 2:** Scrape the anterior part of the gullet of a toad or frog with the back of a scalpel and place the scrapings on a glass slide. Add a drop of 0.65% NaCl solution (this concentration is isotonic to amphibian tissue fluid) and tease the material to shreds with a pair of needles. Place a coverslip and examine it under the microscope. You will see ciliary movements of living ciliated epithelial cells. Next, put a drop of 1% methylene blue solution on the edge of the coverslip. The dye runs under the coverslip. Wipe off the excess dye with a blotting paper and examine the preparation under the microscope. You will observe ciliated epithelial cells with the nuclei stained blue and a row of spine-like cilia.

flattens and broadens the cells of its superficial and middle layers.

### Glands

Glands are secretory structures formed of epithelial tissues. They are of two types: (i) EXOCRINE GLANDS such as salivary, tear, gastric and intestinal glands, possess ducts which conduct their secretions to the respective sites of action. (ii) ENDOCRINE GLANDS such as pituitary, thyroid, parathyroids and adrenals, secrete hormones which pass into the blood instead of flowing out through ducts.

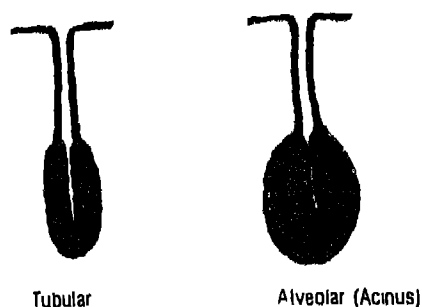
An exocrine gland, with a single unbranched duct is called a SIMPLE GLAND (Fig. 32.4). The duct is lined by epithelial cells. The secretory part of the gland also consists of epithelial cells arranged in the form of tubes (tubules) or sacs (acini, alveoli) or a combination of both. The secre-

tory tubule or acinus may again be coiled or uncoiled, branched or unbranched, and opens into the single duct of the gland. An exocrine gland with a branched system of ducts is called a COMPOUND GLAND (Fig. 32.4). The secretory part consists of many acini or tubules or both. Compound glands are present in the duodenum, pancreas and submandibular salivary glands.

### Connective Tissue

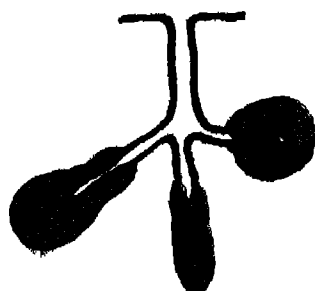
The connective tissue provides the structural framework and support to different tissues forming an organ. It also plays a role in body defence, tissue repair, fat storage and transmission of blood vessels to other tissues. A broad classification of connective tissues is given in Table 32.3.

The connective tissue has a large amount of extracellular material. The



Tubular

Alveolar (Acinus)



Tubulo-alveolar

Fig. 32.4 Types of exocrine glands

A. Simple glands and B. Compound gland

cells lie wide apart. The extracellular material consists of insoluble protein fibres lying in an amorphous, transparent matrix. In blood the extracellular material is a fibre-free fluid. In bones, it is dense, mineralised and rigid. The extracellular and cellular components perform specific functions.



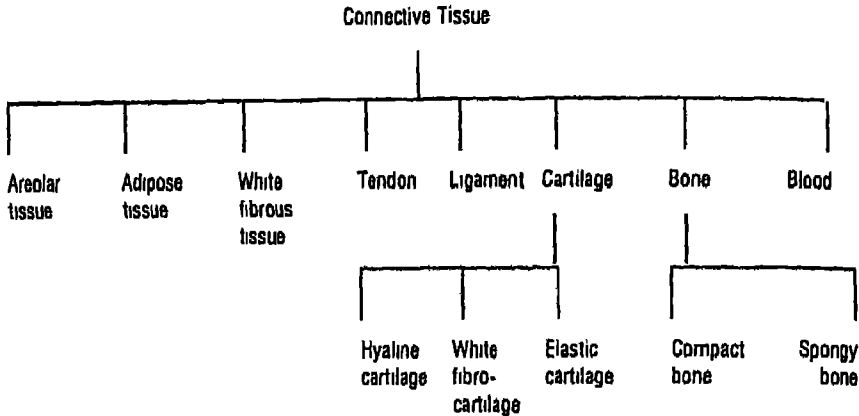
Fig. 32.5 Areolar tissue

### Areolar Tissue

It (Fig. 32.5) occurs beneath the epithelia of many hollow visceral organs, skin and on the walls of arteries and veins. The areolar tissue contains three types of cells—fibroblast, macrophages and mast cells. FIBROBLASTS are the principal cells of this tissue. They are irregularly-shaped flat cells with long protoplasmic processes. Fibroblasts synthesise two kinds of proteins—collagen and elastin. The tensile strength of collagen fibres and the elasticity of elastic fibres prevent displacement and injury of tissues and organs under mechanical stress. Collagen fibres are also laid down at sites of injury and help in tissue repair. Large amoeboid cells called MACROPHAGES are another component of the areolar tissue. They phagocytose and destroy microbes, foreign particles and the cells of damaged tissues. You have studied phagocytosis in Unit Two. Large irregularly ovoid MAST CELLS are also present in the areolar tissue. They store inflammation-producing substances such as histamine in dense granules. These substances, when released from mast cells, help in body defence by

Table 32.3

## CLASSIFICATION OF CONNECTIVE TISSUES



attracting phagocytes to the injured tissue. The areolar tissue joins different tissues, forms the packing between them and helps to keep the organs in place and in normal shape.

in stored fat (Fig.32.6). It occurs mainly

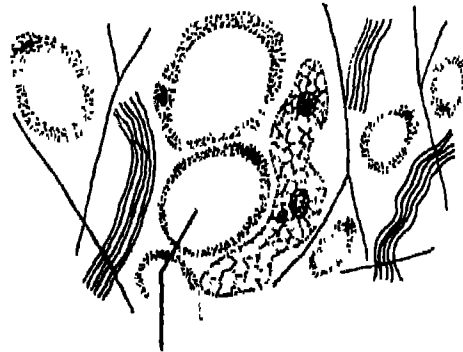


Fig. 32.6 Adipose tissue

You may be aware of allergic reactions in some persons on eating eggs or prawns, or inhaling pollens and spores. These contain chemicals called allergens which stimulate mast cells in certain individuals. The mast cells release excessive amounts of inflammatory substances from their granules. These substances produce extensive dilatation of blood vessels, exudation of fluid in tissues, reddening and swelling of skin, spasms of bronchial or intestinal muscles and other symptoms of ANAPHYLAXIS or ALLERGY. Acute allergies may even be fatal.

**Adipose Tissue**

Adipose tissue is a connective tissue rich

beneath the skin, around kidneys, and in mesentery and bone marrow. Besides fibroblasts, macrophages, collagen fibres and elastic fibres, the adipose tissue also contains large, spherical or oval cells called FAT CELLS or ADIPOCYTES. The cytoplasm and organelles in adipocytes are pressed by fat into a narrow annular layer just beneath the plasma membrane. The adipose tissue synthesises, stores and metabolises fat. It prevents heat loss by

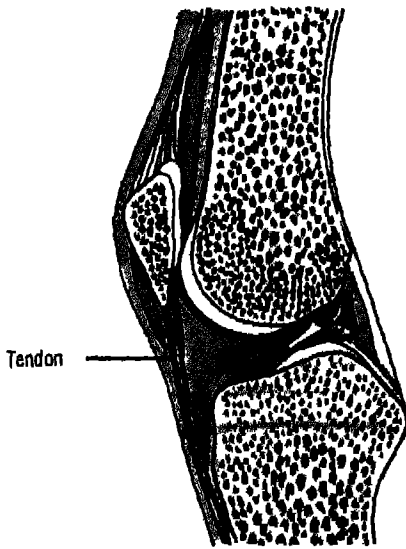


Fig. 32.7 A longitudinal section through the knee joint showing tendon

forming a heat-insulating layer beneath the skin. It forms shock-absorbing cushions around kidneys and eyeballs.

#### White Fibrous Tissue

It carries only a few fibroblasts scattered amidst the dense network of thick collagen fibre bundles. It has great tensile strength. The presence of white fibrous tissue at the joints between skull bones makes them immovable.

#### Tendon *skeletal muscle to bone*

It is a very dense, strong and fibrous connective tissue with thick parallel bundles of collagen fibres. A few flat, elongated tendon cells lie in single rows between the fibre bundles. Tendon forms the strong inextensible attachment of a skeletal muscle to a bone (Fig. 32.7).

#### Ligament *bone to bone*

It is a dense fibrous connective tissue. Its ground substance is densely crowded with collagen fibres running in different direc-

IN HYALINE CARTILAGE, the matrix looks apparently fibre-less and glass-like (hyaline) (Fig. 32.8). It occurs in the larynx, nasal septum, tracheal rings and ribs. It gives those structures a definite but pliable form. WHITE FIBROCARILAGE carries thick dense bundles of collagen

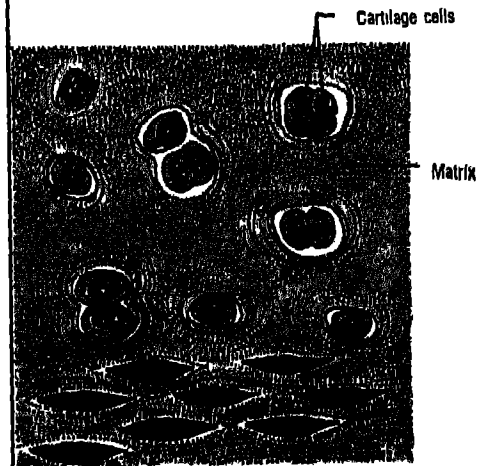


Fig. 32.8 Hyaline cartilage

fibres between rows of chondrocytes in lacunae. It occurs in joints between vertebrae. Its collagen fibres make such joints strong, but less elastic and only slightly movable. ELASTIC CARTILAGE contains a dense network of elastic fibres between scattered chondrocytes. It forms the Eustachian tube, epiglottis and pinna of ear. The elastic fibres make those organs considerably elastic and pliable.

tions, and some elastic fibres. A few elongated flat cells lie between the fibres. The ligament connects bones at the joints and holds them in position.

### Cartilage

Cartilage is a solid but semi-rigid and flexible connective tissue. CHONDROCYTES are large, bluntly angular cartilage cells. They occur in clusters of 2 or 3 cells in small spaces (lacunae) scattered in the matrix.

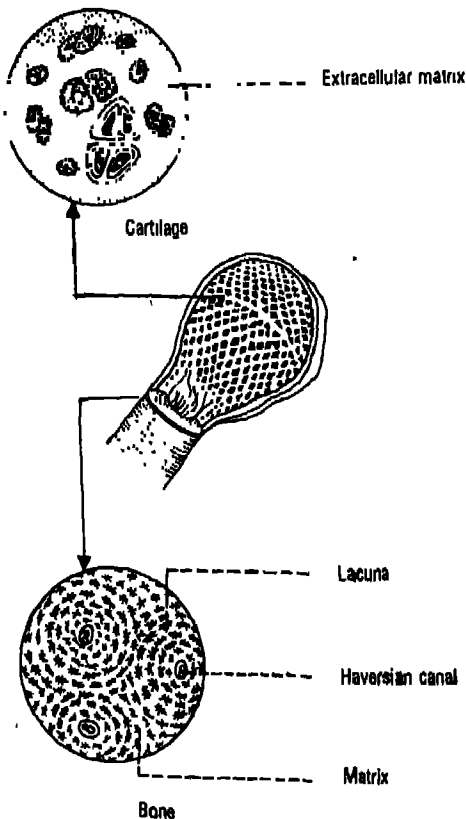


Fig. 32.9 Internal structure of a bone

### Bone

Bone is a solid, rigid and strong connective tissue. Its matrix is heavily deposited with apatite salts of calcium and phosphorus. Flat irregular spaces called LACUNAE occur in the solid matrix. Each lacuna lodges a flat bone cell or OSTEOCYTE. A bone cell has an irregular shape and long cytoplasmic processes. These processes extend into minute canals (CANALICULI) radiating from each lacuna. COMPACT BONE forms the dense outer layers of all bones. It is composed of many parallel, longitudinal, column-like structures called HAVERSIAN SYSTEMS, cemented to each other (Fig. 32.9). In each Haversian system, several concentric layers (LAMELLAE) of bony matrix encircle a longitudinal central canal (HAVERSIAN CANAL). This canal carries blood vessels and nerves. Lacunae containing osteocytes occur in a layer between two lamellae.

SPONGY BONE occurs in the deeper central parts of bones. It carries no concentric organisation like the Haversian system. It consists of a network of many fine irregular bony plates or TRABECULAE. Each trabecula consists of many irregularly-arranged lamellae with lacunae between them.

### Blood

Blood is a fluid connective tissue. Its cells are quite distinct from other connective tissue cells, both in structure and functions. The extracellular material in blood is a fluid devoid of fibres. Fluids outside the cells are generally called EXTRACELLULAR FLUIDS (ECF).

The extracellular material in blood is a

straw-coloured, slightly alkaline (pH 7.4), aqueous fluid called PLASMA. Blood forms about 30-35 per cent of the ECF. The volume of blood in an adult person is about 5 litres.

The total volume of ECF is around 15 litres in a normal adult human. Of the total body water, about 45 per cent is in the form of extracellular fluid and about 55 per cent occurs in the cells as intracellular fluid.

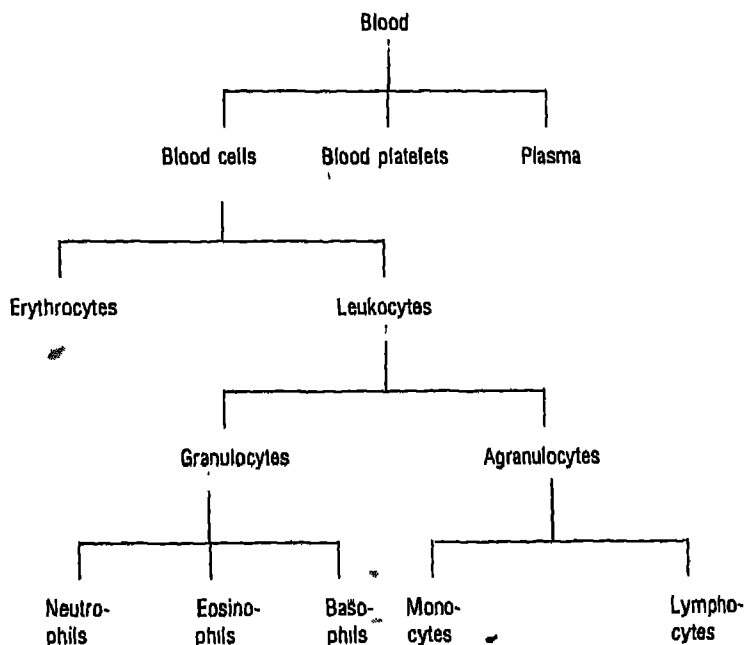
Constituents, having characteristic forms, float in the plasma. They are collectively called the FORMED ELEMENTS of blood. They include the blood cells and

blood platelets. Blood cells are of two types—ERYTHROCYTES and LEUKOCYTES. Blood circulates within blood vessels in higher animals. But other extracellular fluids such as cerebrospinal fluid, interstitial fluid, lymph and aqueous humour occur outside blood vessels.

*Plasma:* Plasma is a slightly alkaline, somewhat viscous aqueous solution containing many organic and inorganic substances. Plasma contains about 92 per cent water and 8 per cent solids. The solutes include glucose, amino-acids, fatty acids, vitamins, enzymes, hormones, antibodies, oxygen, carbon dioxide, lactic acid, and waste products such as urea, uric acid and creatinine.

Table 32.4

## COMPOSITION OF BLOOD



Glucose is a major nutrient in the blood. It occurs in plasma and erythrocytes in similar concentrations. It is added to the blood by intestinal absorption of carbohydrates from food. Liver also adds glucose to blood from stored glycogen, or by forming glucose from amino-acids and lactic acid. Blood glucose is intended for supply to tissue cells. Nearly all BLOOD SUGAR consists of glucose, although very small amounts of other sugars are present. Normal blood sugar level is 80-100 mg per 100 ml of blood in an adult person 12 hours after a meal. Blood sugar rises to a peak 1-1½ hours after a carbohydrate-rich meal, but does not normally exceed 180 mg. Sugar appears in the urine if blood sugar exceeds 180 mg. This happens in diabetes. Fasting lowers the blood sugar to 60 mg or below.

Cholesterol normally ranges from 50 to 180 mg per 100 ml of plasma. It is intended for supply to tissue cells for the synthesis of membrane lipids, vitamin D, steroid hormones and bile salts. Liver synthesises cholesterol and secretes it into blood. It is also added to blood by intestinal absorption from foods like eggs. Eating of saturated fats such as butter, clarified butter (ghee) and hydrogenated vegetable products (vanaspati and margarine) may increase cholesterol synthesis in the body. Metabolic diseases like diabetes, or intake of foods rich in cholesterol and saturated fats may raise the blood cholesterol, leading to heart trouble.

Urea is the major waste product carried in blood. It is also the principal non-protein nitrogenous substance (NPN) in mammalian blood. Its normal range is 17-30 mg per 100 ml of blood. Liver synthesises it during catabolism of amino-acids. Blood transports it to kidneys for excretion in urine. Renal failure or cardiac failure may reduce its urinary elimination. Blood urea then rises to produce toxic effects (UREMIA).

$\text{Na}^+$  and  $\text{Cl}^-$  are, respectively, the principal mineral cation and anion in plasma. Their normal concentrations are, respectively, about 320 and 340 mg per 100 ml of plasma. Smaller amounts of  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{PO}_4^{3-}$ ,  $\text{Fe}^{3+}$ ,  $\text{I}^-$ ,  $\text{Mn}^{2+}$ , etc. are also present in plasma.

Plasma contains three major classes of plasma proteins viz. serum albumin, serum globulins and fibrinogen. Plasma proteins serve as a source of proteins for tissue cells. Tissue cells may utilise plasma proteins for forming their cellular proteins. Additionally, albumin and globulins retain water in blood plasma by their osmotic effects. A fall in plasma proteins leads to filtering out of excessive volumes of water from blood to tissues. This is why

hands and feet get swollen with accumulated fluid (oedema) in persons suffering from dietary deficiency of proteins. Albumin and globulins also transport many substances such as thyroxine and  $\text{Fe}^{3+}$  in combination with them. One class of globulins, called immunoglobulins, act as ANTIBODIES. They inactivate invading microorganisms and their toxins. Some other globulins help to prevent bleeding by changing soluble fibrinogen to insoluble



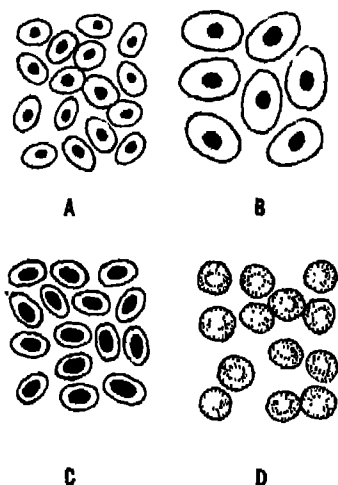


Fig. 32.10 Erythrocytes (RBCs) of different vertebrate animals  
A. Fish; B. Amphibia; C. Bird and D. Mammal

ble fibrin (**BLOOD COAGULATION**). Plasma proteins also maintain the blood pH by neutralising strong acids and bases. Thus, they act as **ACID-BASE BUFFERS**.

To summarise, plasma functions in (a) transport, (b) body immunity, (c) prevention of blood loss, (d) retention of fluid in blood, (e) maintenance of blood pH, (f) uniform distribution of heat all over the body, and (g) conducting heat to skin for dissipation.

**Erythrocytes:** Erythrocytes (red blood corpuscles or RBC) are the most numerous of the formed elements of blood. Their most characteristic feature is the presence of

hemoglobin, the red oxygen carrying pigment. The total number of erythrocytes per microlitre ( $1\mu\text{l} = 1\text{mm}^3 = 10^{-6}\text{l}$ ) of blood is known as the **TOTAL COUNT OF RBC**. It averages 5 millions and 4.5 millions in adult man and adult woman respectively. The total count would be low in anaemia and after profuse bleeding. On the contrary, the abnormal rise in the total count of RBC is called **POLYCYTHEMIA**.

The size and shape of erythrocytes vary in different classes of animals (Fig 32.10). In fishes, amphibians, reptiles and birds erythrocytes are usually nucleated, oval and biconvex. But in mammals they are non-nucleated, biconcave and circular. Only camel and llama possess oval red blood corpuscles. Human erythrocytes measure  $7-8\mu\text{m}$  ( $1\mu\text{m} = 10^{-6}\text{m}$ ) in diameter and  $2\mu\text{m}$  thickness near the rim. The mammalian erythrocyte, when mature, is devoid of all organelles including the nucleus, mitochondria and endoplasmic reticulum. Thus almost the entire volume of the cell is filled with hemoglobin. Moreover, in the absence of organelles, the consumption of oxygen in mature erythrocytes is very low. This spares almost the entire amount of oxygen carried by hemoglobin to be supplied to other cells.

Hemoglobin is a conjugated protein. It is composed of a protein called **GLOBIN**, and an  $\text{Fe}^{2+}$ -porphyrin complex called **HEME**. 100 ml of blood contains about 15 g of hemoglobin. On exposure to a high partial pressure of oxygen in the lungs, hemoglobin is converted to oxyhemoglobin. The latter carries up to 4 molecules of oxygen, loosely bound to its four  $\text{Fe}^{2+}$  ions. At low oxygen pressure in tissues, oxyhemoglobin dissociates into oxygen and deoxyhemoglobin. In this way, erythrocytes transport oxygen from lungs to tissues.

Hemoglobin is the oxygen-carrying pigment in most vertebrates excepting some ice fishes and eel larvae. It also occurs in the blood of some molluscs and annelids; but in these invertebrates, it remains in solution in the plasma itself and is a macromolecule composed of many heme groups. In most invertebrates, instead of hemoglobin other types of oxygen carrying pigments are present. For example, prawns, crabs and some molluscs contain a blue copper-protein complex called HEMOCYANIN in their plasma for oxygen transport; green iron-porphyrin-proteins called CHLOROCRUORINS are the oxygen-carrying pigments in the plasma of some annelids, but their prosthetic groups are different from heme.

Erythrocytes also participate in transporting carbon dioxide from tissues to lungs. Carbon dioxide is partly carried in combination with globin of hemoglobin. But carbon dioxide is mainly carried in both plasma and RBC as bicarbonate ( $\text{HCO}_3^-$ ) which is formed in RBC catalysed by the enzyme CARBONIC ANHYDRASE.

In the foetus, erythrocytes are mainly formed in the liver and spleen. But from birth onwards, erythrocytes are formed in the red bone marrow. Erythrocytes have an average life-span of about 120 days. Iron and proteins are essential raw materials for hemoglobin synthesis while vitamin B<sub>12</sub> and folic acid stimulate maturation of erythrocytes. Therefore, a deficiency of any of these nutrients causes anaemia.

Old and damaged erythrocytes are

If a sample of blood is rendered non-coagulable by adding potassium or sodium oxalate and then centrifuged at a high speed in a graduated centrifuge tube (hematocrit tube), the centrifugal force rapidly sediments the erythrocytes to the bottom of the tube. They become packed into a solid, red, bottom layer while plasma forms a clear, fluid layer above. On the upper surface of the erythrocyte layer, leukocytes form a thin, buff-coloured layer. From the graduations on the tube, the relative volume of erythrocytes may be read as a percentage of the total blood volume. This is called the HEMATOCRIT VALUE or PACKED CELL VOLUME. It normally forms 45 per cent of the blood volume.

The skin and mucous membranes assume a yellowish hue if all the bilirubin cannot be excreted from the body. This condition is called JAUNDICE.

If a sample of oxalated blood is kept undisturbed in a long, narrow graduated tube, erythrocytes sediment slowly from the blood due to gravity. This leaves clear plasma as the supernatant fluid. The rate of such sedimentation is called the ERYTHROCYTE SEDIMENTATION RATE (ESR). It is abnormally enhanced in diseases with abnormal albumin : globulin ratio in the plasma. This is of diagnostic value for many diseases including tuberculosis.

phagocytosed and destroyed by macrophages. The pigment part of hemoglobin is then catabolised to the yellow pigment BILIRUBIN which is excreted in bile. The pale yellow colour of plasma is largely due to bilirubin.

**Leukocytes:** Leukocytes (white blood corpuscles or WBC) are devoid of hemoglobin and are consequently colourless. Leukocytes are nucleated blood cells (Fig. 32.11). They are of two major classes:

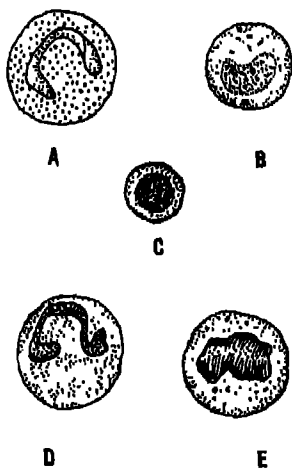


Fig. 32.11 Different types of leukocytes (WBCs)  
A. Eosinophil; B. Basophil; C. Lymphocyte; D. Neutrophil and E. Monocyte

granulocytes (with cytoplasmic granules) and agranulocytes (without granules).

Granulocytes are of three types, viz. neutrophils, eosinophils and basophils, each with lobed nucleus. Agranulocytes are of two types, viz. lymphocytes and monocytes. Neutrophils and monocytes protect the body against microbes by phagocytosing them. Lymphocytes secrete antibodies in the blood to destroy microbes and their toxins. The number of leukocytes per microlitre ( $1\mu\text{l} = 1\text{mm}^3 = 10^{-6}\text{l}$ ) of blood is called the TOTAL COUNT OF WBC. This is normally 5000 in humans. It may rise abnormally in acute infections (e.g. pneumonia), inflammations (e.g. appendicitis) and malignancies (e.g. leukemia). In some conditions such as folic acid deficiency, the total count falls abnormally (leukopenia). The total count of WBC is also of diagnostic value in many diseases.

**Activity:** Sterilise a sharp needle and the tip of your middle finger with rectified spirit. Prick the finger tip and place a drop of blood on a clean glass-slide near one of its ends. Place the edge of another slide in contact with the blood drop at an angle of  $45^\circ$  to the first slide. Push the second slide over the first to draw a thin, uniform blood film. After drying the film in air, stain it with drops of Leishman's stain. Leave the slide covered by a dish for 1 minute. Dilute the dye on the slide by adding an equal number of water drops and allow it to stand for 10 minutes. Next, wash the slide in distilled water, dry it in air and examine under the microscope. Identify and draw the erythrocytes and different types of leukocytes you observe.

**Blood Platelets:** Also called thrombocytes, blood platelets are non-nucleated, round

or oval, biconvex disc-like bodies. They are 2-3 micrometres in diameter and their number normally varies from 0.15 to 0.45 million per microlitre of blood. They bud off from the cytoplasm of very large MEGAKARYOCYTE cells of bone marrow. Their normal life-span is about a week. When a blood vessel is injured, platelets get clumped at the injured spot and release certain chemicals called PLATELET FACTORS. These promote blood coagulation.

*Blood coagulation:* When blood oozes out of a cut, it sets into gel within a few minutes. This is called coagulation. Coagulation is brought about by hydrolysis of soluble fibrinogen of plasma to insoluble fibrin. This is catalysed by an enzyme called thrombin. Fibrin precipitates as a network of fibres. This network traps many blood cells, particularly RBCs, to form a red solid mass called the BLOOD CLOT. The clot seals the wound in the vessel to stop the bleeding. The straw-coloured fluid left after clotting of blood, is called SERUM. The serum cannot be coagulated as it lacks fibrinogen.

THROMBIN occurs in normal blood as an inactive globulin called PROTHROMBIN. It must be activated to thrombin before blood coagulation can occur. In case of injury to a blood vessel, coagulation-promoting substances called THROMBOPLASTINS are released into the blood from clumped platelets and damaged tissues. Thromboplastins help in the formation of the enzyme PROTHROMBINASE. This enzyme hydrolyses prothrombin to thrombin to initiate coagulation.  $\text{Ca}^{2+}$  ions are essential for both the activation and action of thrombin.

Blood normally contains an anticoagulant, HEPARIN which prevents activation

of prothrombin. Heparin is released from mast-cell granules. Blood also contains ANTITHROMBIN which inhibits any thrombin formed accidentally. Moreover, uninjured tissues or platelets do not release thromboplastins. These factors prevent blood coagulation in uninjured blood vessels.

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*Activity:* Prick the tip of your finger with a sterilised needle. Note the time when bleeding starts. Collect some blood immediately into very fine capillary glass-tubes. Start breaking the capillary tube into small bits. Continue this until fibrin threads appear between two broken pieces of the tube. Note the time again. The time-interval called COAGULATION TIME, is an estimate of the coagulating ability of blood.

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Blood drawn from a blood vessel can be kept uncoagulated by adding a pinch of oxalate (sodium or potassium oxalate) to it. Oxalate precipitates  $\text{Ca}^{2+}$  and consequently prevents coagulation. Chilling of blood also delays coagulation because cold depresses the action of coagulation-promoting enzymes.

### Muscle Tissue

Muscles cause movements of limbs and internal organs and also locomotion of the organism. Cells of muscle tissue can shorten forcefully and again return to the relaxed state. This specialised property is called CONTRACTILITY. It is based on the organised arrangement of some protein filaments in the cytoplasm of a muscle cell. The cell shortens or relaxes according to the relative positions of different intracellular filaments. Whenever adequately

Leeches secrete an anticoagulant called **HIRUDIN** in their saliva. When they suck blood from an animal, they pour their saliva into the wound of the victim. As hirudin prevents coagulation of the victim's blood, bleeding continues without interruption. This enables leeches to suck large volume of blood from animals.

Mammalian pancreatic juice contains an enzyme called **TRYPSIN**. It coagulates blood by hydrolysing fibrinogen to fibrin in the same way as thrombin does. This enzyme helps predatory mammals to digest the blood they drink from their prey.

Victims of snake-bites sometimes die of extensive coagulation of their blood, because some snake venoms contain coagulating substances.

stimulated, muscle cells respond by contracting. This property of the muscle tissue is responsible for the various movements in an animal. Muscle cells are usually called **MUSCLE FIBRES** because they are thin and elongated. In higher animals, some muscles remain associated with the skeleton, but many others form walls of visceral organs, blood vessels and heart. Muscle tissue may be classified into striated, non-striated and cardiac muscles, according to their structure, location and functions.

*Striated muscle (Somatic) with Skeleton*

Striated muscle fibres appear to have transverse strips when viewed under the microscope. This is because they show alternate transverse light and dark bands (Fig. 32.12). Most striated muscles are

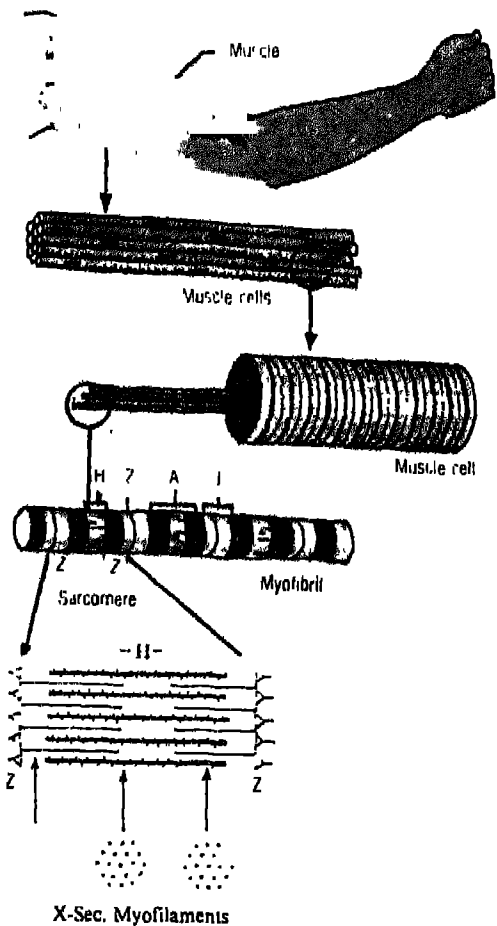


Fig. 32.12 Structure of striated muscle at different levels of magnification (H = H Zone; Z = Z Line; A = A Band; I = I Band)

attached to bones by tendons. They are also called **SKELETAL MUSCLES**. Of the three types of muscles, only striated mus-

cles can be moved at will. Therefore, they are also called **VOLUNTARY MUSCLES**.

A voluntary muscle is composed of long bundles of striated muscle fibres (Fig. 32.12). Each fibre is a long, unbranched, cylindrical cell. It may be as long as 40 mm and as thin as 20 micrometres. It shows transverse striations in the form of regular alternate dark (A) and light (I) bands (Fig. 32.12). At the centre of the I band is a fine, dense, dark band, the Z band or Z-line. The plasma membrane covering the fibre is called **SARCOLEMMMA**. The cytoplasm inside the fibre is called **SARCOPLASM**. The sarcoplasm contains many long, thin, unbranched, cross-striated cylindrical structures called **MYOFIBRILS**. They are arranged along the long axis of the fibre. Dark A bands of neighbouring myofibrils are located side by side; so also are their light I bands. This gives cross-striated appearance to the entire muscle fibre also. Large amounts of energy, needed for contraction, are produced by the oxidation of glucose in the muscle fibre. For this, many elongated oval mitochondria and glycogen granules remain scattered in the sarcoplasm between myofibrils. Each muscle fibre also possesses many elongated, flat nuclei in the superficial sarcoplasm just below the sarcolemma.

Muscle is rich in proteins. Most of these proteins occur as two types of filaments arranged longitudinally in myofibrils. The thick filaments are made up of the protein **MYOSIN**. Myosin filaments are located inside A bands. Thin filaments are more numerous. They are composed of the protein **ACTIN**. From a fine, dense, dark Z band at the centre of each I band, actin filaments extend through the I band and encroach between myosin filaments up to a considerable distance into the A band.

Each segment of the myofibril from one Z band to the next, functions as a contractile unit and is called a **SARCOMERE** (Fig. 32.12).

### *Non-striated or Smooth muscle*

Non-striated muscle fibres do not show cross-striations; instead, they look smooth. Smooth muscles cannot be moved voluntarily. So they are also called **INVOLUNTARY MUSCLES**. Functionally, smooth muscles are of two types. **SINGLE-UNIT SMOOTH MUSCLES** are composed of muscle fibres closely joined together. All its fibres contract together as a single unit. They may contract automatically and rhythmically. Such smooth muscles occur on the walls of hollow visceral organs such as the urinary bladder and the gastrointestinal tract. **MULTI-UNIT SMOOTH MUSCLES** are composed of more independent muscle fibres, not so closely joined together. Individual fibres of such smooth muscles contract as separate units. These occur at hair roots, and on the walls of large blood vessels.

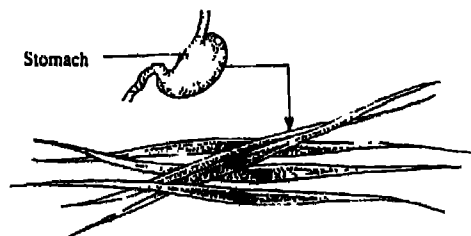


Fig. 32.13 Smooth muscle fibres

Smooth muscle fibres are elongated, spindle-shaped cells. They are packed parallel to each other in branching bundles. Each fibre contains a single, spindle-

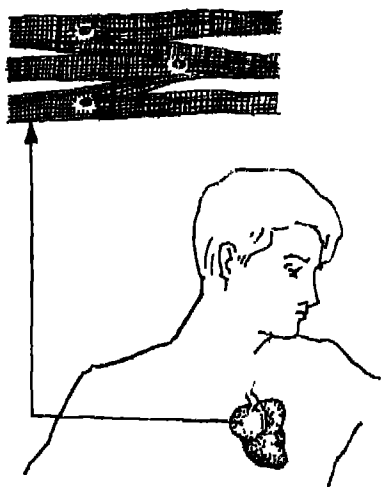


Fig. 32.14 Cardiac muscle fibres

shaped nucleus at its thick central part (Fig. 32.13). The smooth muscle fibre is generally shorter than a striated muscle fibre. Mitochondria and other organelles are less numerous, the sarcoplasmic reticulum is less extensive and protein filaments are not regularly arranged to give rise to striations.

#### Cardiac muscle

Cardiac muscle occurs exclusively in the heart. It possesses considerable automatic rhythmicity and generates its own wave of excitation. The excitation can also pass directly from fibre to fibre in the cardiac muscle. It is not under voluntary control. It shows cross-striations, but striations are much fainter than those of striated muscle.

CARDIAC MUSCLE CELLS are short cylindrical cells joined end to end to form rows. They possess abundant cytoplasm with myofibrils (sarcoplasm) and numerous

mitochondria and glycogen granules. This is because they need a large amount of energy. Faint but regular, alternate dark and light bands gives rise to cross-striations in the cardiac muscle fibres and indicate regular and alternate arrangements of thin and thick filaments in the fibre. Sarcomeres are also present. Cardiac muscle cell frequently branches to form junctions with neighbouring cells (Fig 32.14). Where two cardiac muscle cells meet end to end, dense zig-zig junction is formed between them. It is called an INTERCALATED DISC.

#### Nerve Tissue

In multicellular organisms some cells become specialised for receiving and transmitting information and messages. Changes outside or inside the body act as stimuli and initiate their activity. The cells react by changing the pre-existing potential differences across their plasma membrane and by conducting this potential change like a wave along their membrane. This property of the cells is called EXCITABILITY. Cells of the nerve tissue are called NEURONS. The potential changes propagated along their membrane is called a NERVE IMPULSE. It serves as a message passed on either to other neurons or to muscles and glands. The response elicited may be sensation such as pain, or an action like muscle contraction or glandular secretion.

The brain and the spinal cord, collectively known as the CENTRAL NERVOUS SYSTEM (CN system), the PERIPHERAL NERVES and NERVE GANGLIA outside the CN system are all made up of the nerve tissue. Ordinary connective tissue is absent inside the central nervous system; the neurons are held together by supporting cells called NEUROGLIAL CELLS. Nerve

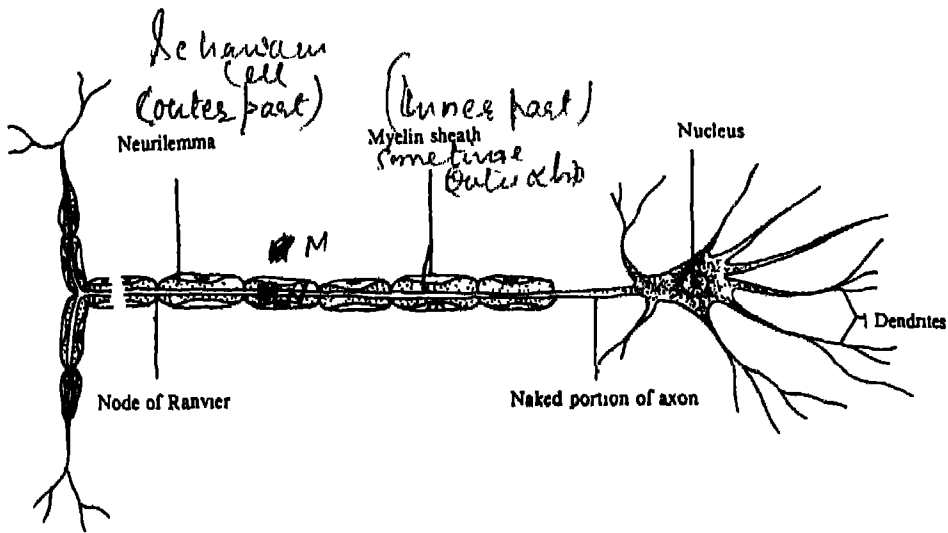


Fig. 32.15 A neuron with myelinated axon

tissue is made of neurons and neuroglia cells.

A NEURON (Fig 32.15) has a large cell body with two or more, thin protoplasmic processes extending from it. One of the processes called the AXON is long and conducts nerve impulses away from the cell body. It ends in a number of small branches on muscle fibres, gland cells or other neurons. The remaining one or more processes conduct nerve impulses towards the cell body and are called DENDRITES or DENDRONS. The axon terminals may form inter-communicating junctions, called SYNAPSES, with dendrite terminals, cell bodies or even axons of other neurons. Nerve impulses pass between neurons through the synapse with the help of chemicals such as acetylcholine which are termed NEUROTRANSMITTERS.

The cell body of a neuron is called the PERIKARYON or SOMA. The soma has various shapes. Both the soma and the processes are covered by the plasma mem-

brane. The soma contains abundant granular cytoplasm and a large nucleus. To serve the high energy needs for impulse conduction, neurons have very many mitochondria. Light microscopy shows many small conical, angular or rhomboidal and highly basophilic structures in the cytoplasm of soma and dendrites; they are called MYSEL BODIES and are absent in the axon and the axon hillock.

The extended axon or dendrite of a neuron is called a NERVE FIBRE. Nerve fibres are collected into bundles in a nerve in the way as the muscle fibres in a muscle. Each nerve fibre is covered with a continuous sheath, called the NEUROLEMMMA. The neurolemma sheath is made up of a single layer of flat expanded SCHWANN CELLS. Some nerve fibres are covered by a lipid-rich insulating layer, called the MYELIN SHEATH. Such nerve fibres are called MYELINATED or MEDULATED NERVE FIBRES. Each myelinated nerve fibre (Fig. 32.15) shows constric-



tions at regular intervals called **NODES OF RANVIER**, these result from interruptions in the myelin sheath at those places.

Some nerve fibres are not covered by myelin sheath. They are called **NON-MYELINATED NERVE FIBRES**. They do not possess nodes of Ranvier. Myelinated fibres are generally thicker than

non-myelinated ones.

There is no neurolemma inside the central nervous system. In the absence of Schwann cells, myelin is formed there by the spiral wrapping of the nerve fibre by processes of OLIGODENDROCYTES. They are one type of neuroglia cells.

## SUMMARY

The body of a multicellular animal is made of many types of cells. The cells are separated by or bound together by extracellular material. A tissue is made up of one or more types of cells set in extracellular material. Each tissue has specific function.

Cells not widely separated are often held together by cell junctions.

Animal tissues include epithelial tissue which covers free surfaces, connective tissue which holds other tissues together, muscular tissue which carries out movement and locomotion, and nerve tissue which conducts information as propagated potential changes. An organ may be made up of more than one type of tissue performing specific functions. An organ-system consists of several organs whose coordinated activities help to carry out a major biological process. The major organ-systems are those which concern with digestion, respiration, circulation, excretion, locomotion and movement, reproduction, nervous and hormonal coordination.

Simple epithelium may be of several types, viz. cubical, squamous, columnar, pseudostratified and ciliated. Compound epithelium may be stratified or transitional. Stratified epithelium covering the skin has its superficial cell layer heavily keratinised and protects the underlying tissues from mechanical abrasions.

Glands have secretory function. Exocrine glands have ducts for conducting secretions to the sites of action. Endocrine glands have no ducts and secrete hormones into the blood.

The connective tissue holds other tissues together. It contains large amount of extracellular materials. The extracellular material may be rich in fibres, or deposited with mineral salts, or fluid. The areolar connective tissue forms the supporting framework of organs. It is made of several types of cells, e.g. fibroblasts, macrophages and mast cells, and some types of fibres such as white collagenous and yellow elastic fibres. The areolar connective tissue imparts tensile strength as well as elasticity to organs to protect them from injury under mechanical stress. The adipose tissue stores fat in its cells, the adipocytes. White fibrous tissue occurs at immovable joints and in capsules over organs and carries a few fibroblasts scattered amidst thick collagen fibre bundles. Tendon forms the inextensible attachment of a muscle to a bone. Ligaments connect bones at joints. Cartilage is a solid but flexible connective tissue with cartilage cells in lacunae or spaces in its matrix. Bone is a solid and rigid connective tissue. Its matrix is hardened by deposits of calcium and phosphate. Bone cells are located in lacunae scattered in the matrix. Bones form the supporting framework of

the body and protect soft internal organs and viscera. Blood is fluid connective tissue composed of blood cells, blood platelets and an extracellular fluid called plasma. Red blood cells are non-nucleated in adult mammals and transport oxygen and carbon dioxide. White blood cells are nucleated and possess granular or non-granular cytoplasm. They help in body defence. Blood platelets help in blood coagulation. Plasma transports many nutrients like glucose and amino-acids, waste-products like urea, respiratory gases and many other substances. Plasma carries certain proteins. Albumins and globulins help to maintain the osmotic pressure of plasma, fibrinogen coagulates into fibrin during bleeding to prevent blood loss and some globulins act as antibodies.

Muscle tissue is made of muscle fibres whose contractions and relaxations bring about movements and locomotion. Striated or skeletal muscles can be moved voluntarily. They mostly occur in association with bones. They bear cross-striations in the form of alternate dark (A) and light (I) bands. The muscle fibre contains many cylindrical myofibrils. In each myofibril, contractile filaments of proteins called actin and myosin are arranged in a regular order. This gives the cross-striated appearance to the myofibril and also to the muscle fibre. Smooth muscles occur on viscera, internal organs and blood vessels. Smooth muscle fibres are elongated, spindle-shaped and mono-nucleated. They show no cross-striations and cannot be worked voluntarily. Cardiac muscle forms the walls of heart chambers.

Nerve tissue receives and transmits information and messages in the form of nerve impulses which are propagated potential changes. This tissue is composed of neurons and neuroglia cells. Each neuron has a large cell body with two or more processes extending from it. One of the processes carries nerve impulses away from the cell body and is called the axon; other processes carry nerve impulses towards the cell body and are called dendrites. The axon forms intercommunicating junction, called synapses with dendrites and cell body or axon of some other neuron. The cell body carries in its cytoplasm many small basophilic granules called Nissl granules or bodies which are folded aggregates of rough endoplasmic reticulum. The extended axon or dendrite is called a nerve fibre. It is covered by a continuous neurolemma sheath outside the central nervous system. Besides, some nerve fibres are also covered by a myelin sheath. The myelin sheath is interrupted at regular intervals forming nodes of Ranvier. Such nerve fibres are called myelinated nerve fibres. Neuroglia cells hold the neurons in position in the central nervous system.

## QUESTIONS

1. Match the terms in column I with those in column II:

### Column I

- (a) Stratified keratinised squamous epithelium
- (b) Exocrine gland
- (c) Polycythemia
- (d) Node of Ranvier
- (e) Dendrite

### Column II

- (i) Nerve impulse
- (ii) Erythrocyte
- (iii) Transitional epithelium
- (iv) Megakaryocyte
- (v) Tear

Handwritten annotations and lines indicating matches:

- A line connects (c) Polycythemia to (ii) Erythrocyte.
- A line connects (d) Node of Ranvier to (i) Nerve impulse.
- A line connects (e) Dendrite to (iii) Transitional epithelium.
- A line connects (iv) Megakaryocyte to (v) Tear.
- Handwritten text next to (ii) Erythrocyte: "abnormal increase in RBCs".
- Handwritten text next to (iii) Transitional epithelium: "in bladder".

- (f) Blood coagulation  
 (g) Blood platelet  
 (h) Macrophage  
 (i) Urinary bladder  
 (j) White fibrous tissue  
 (k) I band
- (vi) Collagen fibres  
 (vii) Phagocytosis  
 (viii) Skin  
 (ix) Actin  
 (x) Trachea  
 (xi) Prothrombin  
 (xii) Myelinated nerve fibre
2. Distinguish between:  
 (a) A band and I band  
 (b) Plasma and serum  
 (c) Simple epithelium and compound epithelium  
 (d) Cardiac muscle and striated muscle  
 (e) Neuron and neuroglia  
 (f) Simple gland and compound gland  
 (g) Nerve fibre and muscle fibre  
 (h) Single-unit smooth muscle and multi-unit smooth muscle  
 (i) White collagen fibres and yellow elastic fibres  
 (j) Tendon and ligament  
 (k) Myelinated nerve fibres and non-myelinated nerve fibres
3. Name the tissues where the following structures occur:  
 (i) Fat cell (ii) Haversian canal (iii) Myofibril (iv) Axon (v) Schwann cell  
 (vi) Fibroblast (vii) A band (viii) Chondrocyte
4. Mark the odd one in each series:  
 (a) Areolar tissue; blood; neuron; tendon  
 (b) Prothrombin; heparin; fibrinogen; thromboplastin  
 (c) Salivary gland; gastric gland; tear gland; thyroid gland  
 (d) Neurolemma; dendrite; Z band; myelin
5. Describe the microscopic structure of the following with diagram:  
 (i) Compact bone (ii) Stratified epithelium (iii) Adipose tissue (iv) Striated muscle fibre (v) Cardiac muscle cell (vi) Stratified squamous epithelium
6. How do erythrocytes transport oxygen and carbon dioxide in the blood?
7. Name the major classes of plasma proteins and describe their functions.
8. What are the following things? Where do you find them in the animal body?  
 (i) Osteocytes (ii) Nissl bodies (iii) Hemoglobin (iv) Haversian system (v) Canaliculi (vi) Ciliated epithelium (vii) Brush-bordered columnar epithelium (viii) Single-unit smooth muscles (ix) Lacunae (x) Nodes of Ranvier
9. How does blood get coagulated on coming out from an injured vessel? How is coagulation normally prevented in an uninjured vessel?
10. Fill in the blanks:  
 (a) A tendon attaches a muscle to a bone  
 (b) Pseudostratified epithelium lines the trachea tract while transitional epithelium lines the urinary tract.  
 (c) Dark bands of muscle fibres are made of the protein myosin while light bands are composed of actin.

- (d) Nerve impulses come to the cell body of a neuron along its dendrites and goes away from the cell body along its axon.
- (e) Lacunae of bones house osteocytes while lacunae of cartilages contain chondrocytes.
- (f) Tendon contains bundles of collagen fibres and rows of tendon cells cells between them.

11. Write whether the following statements are true or false:

- (a) Stratified squamous epithelium covers moist surfaces like buccal cavity. F <sup>skin</sup>
- (b) Fibroblasts store fat in the adipose tissue. F <sup>synthesise proteins collagen</sup>
- (c) Serum albumin acts as antibody to help in body defence. F <sup>it is globulin</sup>
- (d) Transitional epithelium prevents loss of water from the blood to the urine. F <sup>it is water</sup>
- (e) Blood platelets are formed from macrophages. F <sup>from megakaryocyte</sup>
- (f) Nodes of Ranvier occur in non-myelinated nerve fibres. F
- (g) Single-unit smooth muscle fibres may contract automatically and rhythmically. T
- (h) Sarcomere is a segment of striated muscle fibre between consecutive Z bands. T

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**ANIMAL NUTRITION**

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NUTRITION is the procurement of substances necessary for growth, maintenance and activities of a living body. Energy is required for synthesising organic molecules, forming biological structures and running life processes. This energy is obtained either directly as light photons from sunlight or indirectly as chemical bond-energy of molecules taken in food. Green plants can directly utilise the energy of sunlight to synthesise organic molecules such as sugars from inorganic substances. Such form of nutrition utilising directly the energy of sunlight is called AUTOTROPHIC MODE OF NUTRITION. In contrast, animals must acquire energy in the form of bond-energy of organic molecules synthesised by plants. They derive organic food materials by consuming bodies or products of other living or dead plants or animals. This form of nutrition is called HETEROTROPHIC NUTRITION. Ultimately, all animals get their energy from sunlight through plants.

**HETEROTROPHIC NUTRITION**

Heterotrophic nutrition is of two main types — holozoic and saprozoic. All vertebrates and many invertebrates eat whole plants, whole animals or their parts. During digestion they partly hydrolyse the large organic molecules with the help of enzymes. The digested material is subsequently absorbed into cells and utilised. This is known as HOLOZOIC NUTRITION. In SAPROZOIC NUTRITION a living organism thrives on decaying organic materials of plant or animal origin. The organism secretes enzymes to the surrounding medium to hydrolyse such materials into simple and soluble products and absorbs them through the body surface.

**Digestion**

The complex and large organic molecules of plant or animal origin, which may be consumed by animals have to be converted into simpler and smaller molecules before they can enter into cells. Digestion breaks large molecules of organic nutri-

ents into smaller molecules, and less soluble or insoluble molecules into soluble ones. This is necessary for the entry of those molecules into the protoplasm of the cell. Small and water-soluble molecules such as glucose and vitamin C need not be digested before they enter a cell.

Digestion is carried out mostly by cleaving covalent bonds in nutrient molecules by hydrolysis, using a molecule of water for the cleavage. Digestion is carried out by enzymes, called HYDROLASES.

In many lower organisms, particularly unicellular protists like amoeba, the cell engulfs food materials by endocytosis. They are then digested by the enzymes inside the cell. The digested products pass to the cytoplasm across the endocytotic vesicle membrane. Such digestion is called INTRACELLULAR DIGESTION. Intracellular digestion also occurs in some multicellular animals.

With the evolution of multicellularity, intracellular digestion has been progressively replaced by EXTRACELLULAR DIGESTION. In extracellular digestion, a cell usually synthesises one or a few digestive enzymes for digesting only a specific type of nutrient. These enzymes are secreted into the surrounding medium. Food materials are digested outside the cells and the products are then absorbed into the cells.

For more effective extracellular digestion, multicellular animals ingest the food into relatively narrow cavities or canals, enclosed in the body but communicating with the exterior. Food is digested extracellularly by enzymes secreted into that cavity or canal. A complex alimentary canal has progressively evolved for extracellular digestion in higher invertebrates and vertebrates. The alimentary canal has acquired separate openings for food ingestion

and for elimination of undigested remnants. This enhances the efficiency of digestion and absorption. The canal is divided into different chambers and specific enzymes are secreted for digesting specific nutrients in each chamber. Cells secreting digestive enzymes are either located on the walls of these chambers or collected in digestive glands (e.g. salivary glands and pancreas).

#### *Alimentary or Digestive system*

It consists of an alimentary canal and its associated glands. Food is taken into the alimentary canal through the mouth and is propelled along by the movements of muscles on its wall. Glands located on its wall as also in some associated organs, secrete enzymes and other digestive materials into the lumen of the canal. After extracellular digestion the products are absorbed into the cells on its wall. The unabsorbed food remnants are passed out from the alimentary canal by a process called EGESTION. The alimentary system differs widely in different animals in spite of the basic similarities in structure and functions. Let us study two instances, one in the invertebrate prawn and the other from mammals.

**Alimentary System of Prawn:** It consists of an alimentary canal and a single digestive gland called the HEPATOPANCREAS (Fig. 33.1). The ALIMENTARY CANAL is divided into the foregut, the midgut and the hindgut. The FOREGUT consists of a small BUCAL CAVITY, a broad muscular tube called OESOPHAGUS and a sac-like STOMACH. The foregut communicates with the exterior through the mouth. Ingested food is moved to the stomach by the movements of muscles on the oesophageal wall. The food is crushed between cuticular plates

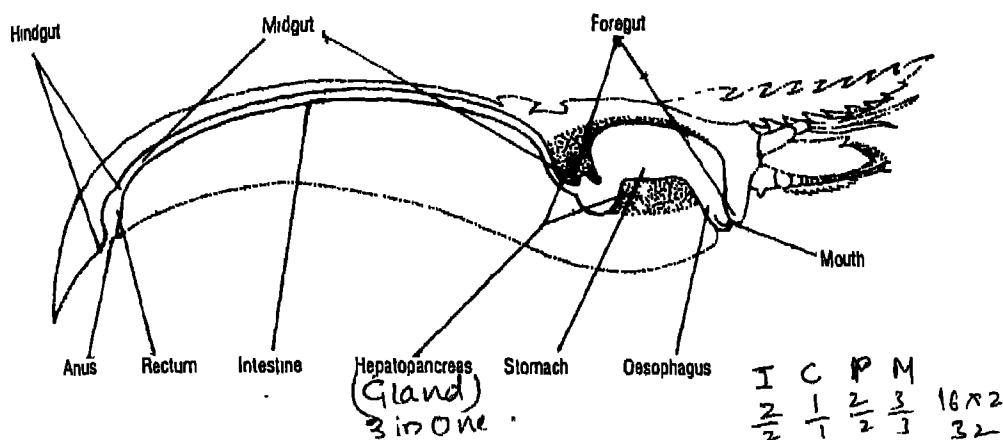


Fig. 33.1 Alimentary system of prawn (lateral view)

on the stomach wall by the movements of the stomach. The duct from hepatopancreas opens into the stomach. The enzymes of the hepatopancreatic juice digest foods in the stomach. The food then passes from the stomach to the MIDGUT. Digested foods are absorbed from the stomach and the midgut and stored in the hepatopancreas. The remaining undigested food passes to the HINDGUT and remains stored temporarily in its swollen muscular chamber called the RECTUM. Finally, it is eliminated by egestion through the ANUS. Midgut and hindgut constitute the intestine.

The hepatopancreas is a gland located around the stomach and the midgut. It serves the roles of pancreas, intestinal glands and liver of higher animals. It secretes enzymes for digesting carbohydrates, lipids and proteins. It also stores the absorbed nutrients.

**Mammalian Alimentary System:** All mammals possess a muscular tongue in the floor of the buccal cavity (Fig. 33.2). It helps in INGESTION, chewing and swallowing of foods and also bears taste buds

which perceive the tastes of foods. Most mammals possess teeth on their jaws. The root or roots of each tooth are set into cavities, called tooth sockets on jaws. The number and types of teeth vary from species to species. An adult human being has 16 teeth on each jaw. In each half of jaws starting from the middle and going backwards, there are two incisors, one canine, two premolars and three molars (2+1+2+3). Incisors are shaped like a chisel and possess sharp cutting edges. Canines are shaped like a dagger and pierce the food; they are very large and well-developed in predatory mammals. Premolars and molars are broad, strong crushing teeth. With the help of the teeth, tongue and jaw movements, food is chewed and mixed with saliva in the mouth.

Three pairs of salivary glands, viz. parotids, submaxillary (submandibular) glands and sublingual glands secrete saliva which reaches the mouth through their ducts (Fig. 33.3). In a few mammals, including man and pig, saliva contains a starch-digesting enzyme. Mucin in saliva helps to lubricate the food for

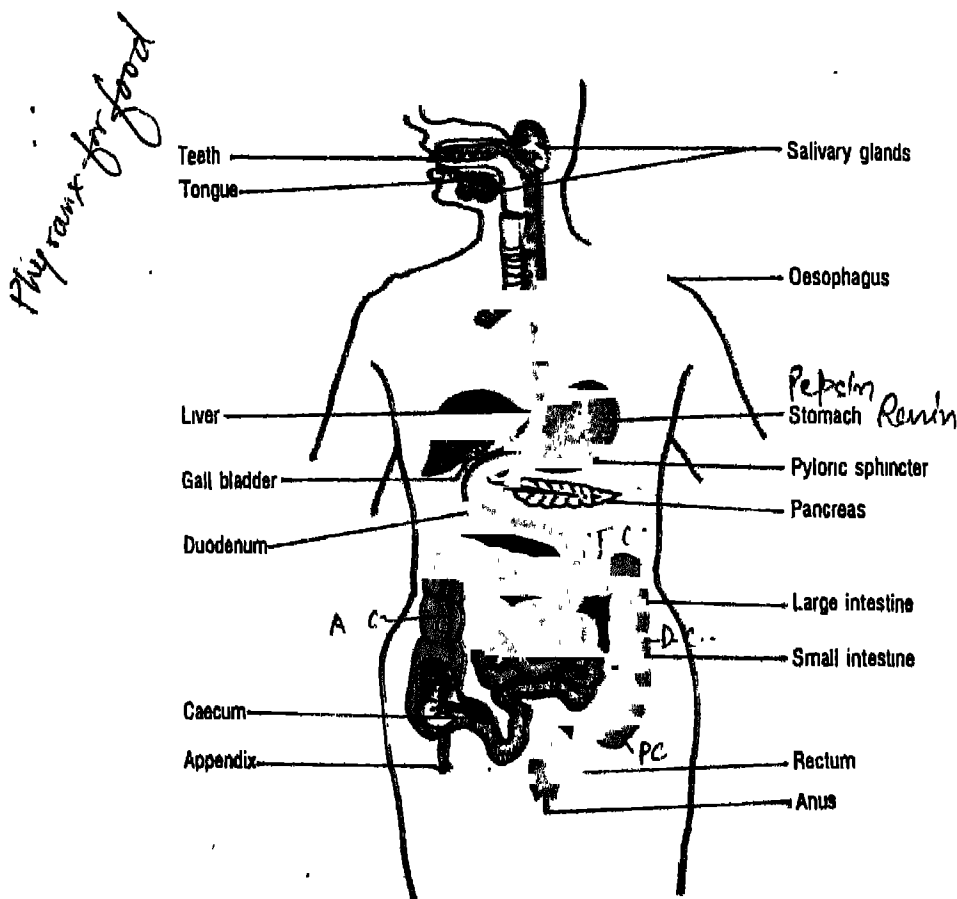


Fig. 33.2 Alimentary system of man

swallowing.

The mouth leads to a funnel-shaped pharynx which communicates with a long muscular tube-like oesophagus (Fig. 33.2). The oesophagus opens into the stomach. The swallowed food is propelled towards the stomach through the oesophagus by the movements of its muscular wall.

The stomach is a large muscular sac. It is somewhat J-shaped in a human being and occupies the left side of the abdomen. The oesophagus opens at the cardiac end of the stomach while the pyloric end

(antrum) of the stomach opens into the small intestine. The stomach has many glands on its wall. The cells of these glands secrete HCl, protein-digesting enzymes (pepsin and rennin) and mucin in the lumen of the stomach. The mixture of their secretions in the gastric lumen is called GASTRIC JUICE. It digests proteins in the stomach. The muscles on the stomach wall churn and mix the food with the gastric juice. They also propel the food to the small intestine through the pyloric end.



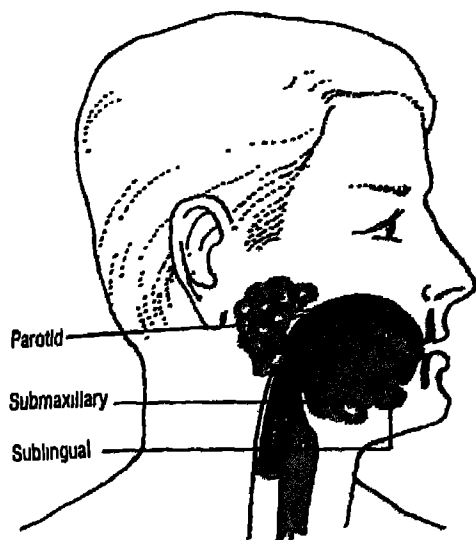


Fig 33.3 Locations of salivary glands in man

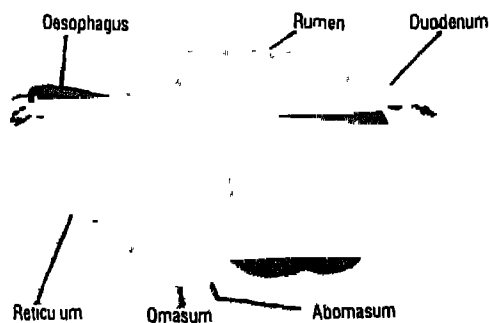


Fig 33.4 Compound stomach of a ruminant animal (Arrows indicate the passage of food through it)

Ruminant animals such as cattle, buffalo, sheep, goat and camel have a COMPOUND STOMACH. It consists of four

A traumatic wound in the abdomen of a man, named St Martin, resulted in a permanent opening in his stomach wall. As the lumen of his stomach could be reached through the holes in the walls of his abdomen and stomach, scientists used him to study gastric secretion and digestion in the intact human stomach.

I. P. Pavlov, the eminent Russian physiologist, cut a piece of gastric mucosa from the stomach of a dog. He made a pouch of the cut piece of mucosa. The pouch was connected to the main stomach by a muscle band along which it received the nerve fibres and blood vessels. The pouch was opened to the exterior through an opening in the abdominal wall. But the lumen of the pouch did not communicate with the main stomach. It was called PAVLOV'S POUCH and was extensively used by Pavlov in studying the effects of feeding on gastric secretion.

chambers, viz. RUMEN, RETICULUM, OMASUM and ABOMASUM (Fig. 33.4). Some ruminants like camel and deer, however, do not have omasum. Rumen is the first and the largest of the four chambers. Rumen and reticulum harbour numerous bacteria and protozoa, which carry out extensive fermentation of cellulose. So, these two chambers function as sites for cellulose digestion in ruminants. Food passes from rumen and reticulum to omasum which concentrates the food by absorbing water and bicarbonates. Finally, the food reaches the fourth chamber, abomasum. This is the true stomach

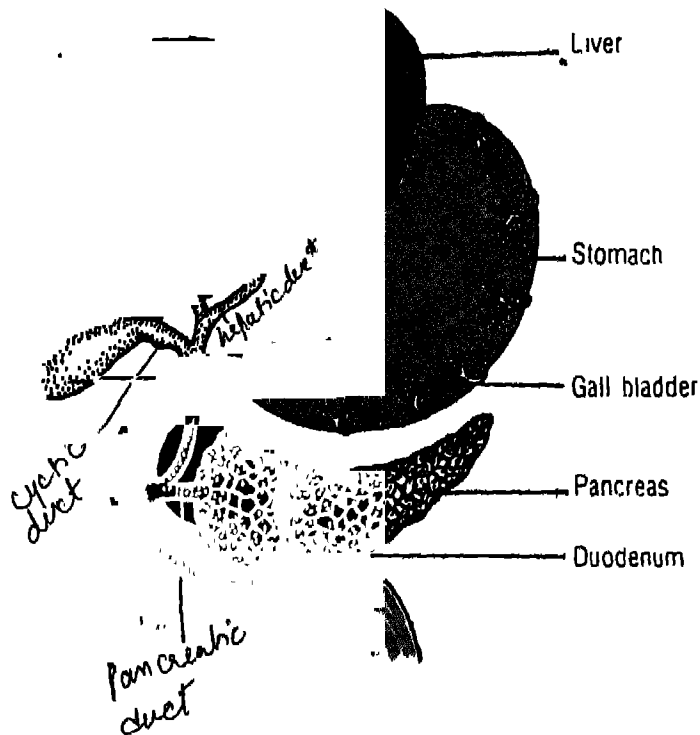


Fig 33.5 A portion of human alimentary system showing locations of liver, pancreas and gall bladder

and secretes gastric juice containing HCl and pepsin. The other three chambers do not secrete gastric juice. From abomasum, the food passes to the small intestine.

The small intestine of mammals is a long, highly coiled, narrow tube. Its wall puts out numerous long, finger-like projections into its lumen. These projections called VILLI increase the surface area of the intestinal mucosa and consequently enhance absorption.

In higher mammals like man the small intestine is usually distinguished into three parts, viz. DUODENUM, JEJUNUM and ILEUM. Each part has distinctive microscopic structure. Duodenum, the first part, is U-shaped. The common bile duct opens into it and drains juices from pancreas and liver. The jejunum follows duodenum and is longer and more coiled. The last part or ileum is also highly coiled and opens into the large intestine. All the

three parts of the small intestine have many tube-like glands in their wall. These glands secrete intestinal juice into the intestinal lumen. This juice contains a number of enzymes for digesting various types of food. The muscles on the intestinal wall churn, knead and crush the food, mix it with intestinal juices and propel it towards the large intestine by their contractions. The digested products are absorbed mostly from the small intestine.

PANCREAS is located in the bend of the duodenal loop (Fig. 33.5). It secretes PANCREATIC JUICE, rich in enzymes for digesting starch, lipids, proteins and nucleic acids. The pancreatic juice is released into the pancreatic duct which joins the common bile duct. The LIVER is the largest gland of the body (Fig. 33.5). It is located in the right upper part of the abdomen just below the diaphragm. It secretes BILE containing BILE PIGMENTS and organic salts, called BILE SALTS. The bile salts help in digesting and absorbing fat. The secreted bile passes from the liver through the hepatic ducts to the common bile duct which opens into the duodenum. If the intestine contains no food, the bile flows through a cystic duct to the gall bladder instead of flowing into the duodenum. The GALL BLADDER is a small elongated, muscular sac below the liver. It stores bile. When food comes into the small intestine, the gall bladder contracts to expel the stored bile into the intestine through the cystic duct and the common bile duct. Do you know that a horse has no gall bladder?

Digestion of different nutrients is completed in the small intestine by the action of pancreatic juice, intestinal juice and bile. The end products of digestion are then absorbed from the small intestine.

The small intestine opens into the

LARGE INTESTINE. It is much shorter and much wider than the small intestine. It shows neither villi nor brush-bordered cells unlike the small intestine. The large intestine has three parts — CAECUM, COLON, and RECTUM. The caecum is very large and spacious in herbivores such as horse and ass. But in man it is reduced to a small pouch-like part below the opening of the ileum into the large intestine. Human COLON consists of an ASCENDING COLON, a TRANSVERSE COLON, a DESCENDING COLON and a PELVIC COLON. The pelvic colon continues into the rectum which opens to the exterior through the anus. The large intestine secretes no enzyme and plays only a minor role in the absorption of nutrients. The large intestine serves to store unabsorbed food remnants temporarily. It also concentrates the contents by absorbing water to form faeces. The movements of the colon help to void the faeces through the anus. This is known as EGESTION.

In herbivores numerous bacteria live in the spacious caecum and colon, and ferment cellulose. So, in such animals, the large intestine is important for cellulose digestion. Rabbit - *ty.*

### *Digestion of Carbohydrates*

For many herbivorous animals, the cellulose of the plant foods is the principal source of carbohydrate. But vertebrates have no enzyme to digest cellulose. They have to depend on SYMBIOTIC DIGESTION of cellulose by microorganisms harboured in their digestive tracts. Man and animals, subsisting on cereal grains, fruits, or tubers, consume carbohydrate mainly in the form of starch. They also consume some disaccharides such as sucrose (cane sugar) and lactose (milk sugar) in food. Starch and disaccharides are digested by

Table 33.1

## THE MAJOR GASTROINTESTINAL ENZYMES IN MAMMALS

Juice	Enzyme	Site of Action	Substrates	Products
Saliva	Ptyalin	Mouth, Stomach	Starch, dextrins, glycogen	'Limit' dextrins, maltose, isomaltose
Gastric Juice	(a) Pepsin	Stomach	Proteins Casein (milk)	Peptones, Paracasein (curd)
	(b) Rennin	do	Casein	Paracasein
Pancreatic Juice	(a) Amylase	Small Intestine	Starch, dextrins, glycogen	'Limit' dextrin, maltose, isomaltose
	(b) Trypsin	do	Proteins Chymotrypsinogen (inactive),	Peptides, Chymotrypsin (active)
			Procarboxypeptidases (inactive)	Carboxypeptidases (active)
			Proelastase (inactive)	Elastase (active)
			Fibrinogen (blood)	Fibrin (clot)
	(c) Chymotrypsin	Small intestine	Casein (milk)	Paracasein (curd)
	(d) Carboxypeptidases	do	Peptides	Smaller peptides, amino-acids
	(e) Lipase	do	Triglycerides	Monoglycerides, Fatty acids
	(f) DNase	do	DNA	Deoxyribonucleotides
	(g) RNase	do	RNA	Ribonucleotides
Intestinal juice	(a) Enteropeptidase (Enterokinase)	Small intestine	Trypsinogen (inactive)	Trypsin (active)
	(b) Aminopeptidases	do	Peptides	Smaller Peptides, Amino-acids
	(c) Dipeptidases	do	Dipeptides	Amino-acids
	(d) Isomaltase	do	'Limit' dextrins, isomaltose	Glucose
	(e) Maltase	do	Maltose	Glucose
	(f) Sucrase	do	Sucrose	Glucose, fructose
	(g) Lactase	do	Lactose	Glucose, galactose
	(h) Lipase	do	Triglycerides	Monoglycerides, Fatty acids
	(i) Nucleotidase	do	Nucleotides	Nucleosides, Inorganic phosphate
	(j) Nucleoside phosphorylases	do	Nucleosides + phosphate	Purine/pyrimidine, Pentose phosphate

CARBOHYDRASES of the alimentary system.

Man secretes a starch-hydrolysing enzyme in the saliva, it is called SALIVARY AMYLASE or PTYALIN. But ptyalin is absent in the saliva of many animals including domestic herbivores like cows and buffaloes, and predatory carnivores such as tigers and lions. Interestingly, pigs consume roots and tubers containing stored starch, and secrete ptyalin in their saliva. Chewing food helps in ptyalin action, because it mixes the food with saliva. It also breaks food particles into smaller particles with greater surface area exposed to ptyalin action. Cooking vegetable foods causes breaches in the cellulose cell walls of plant cells to enable ptyalin to enter and digest the starch. Ptyalin causes hydrolysis of starch into disaccharides—maltose and isomaltose and small dextrins, called 'limit' dextrins.  $\rightarrow$  Glucose.

About 30 per cent of the food starch is hydrolysed in the mouth. If you chew a piece of bread slowly, it will taste sweeter after some time. This is due to the production of the sweet tasting maltose from starch by ptyalin. Ptyalin reaches the stomach mixed with the swallowed food. There it continues digesting starch for some time. The hydrochloric acid present in the gastric juice destroys all ptyalin in a short while. The gastric juice contains no carbohydrate-digesting enzyme.

**Activity:** Boil some starch in water. Cool and pour the starch solution into three test tubes labelled A, B and C. Add a drop of dilute iodine solution to each test tube. Introduce some saliva to test tubes A and B and some water to test tube C. Put a few drops of dilute HCl to tube B. Shake

the tubes and keep them standing at the room temperature in summer or in a water bath at 37-38°C in winter. Note the change of colour in the test tubes every 10 minutes. The blue colour changes to reddish violet and gradually disappears in tube A as ptyalin hydrolyses starch to dextrins. The blue colour of iodine persists in test tube B, because HCl destroys ptyalin and prevents starch hydrolysis. In test tube C also the blue colour of starch solution remains unchanged, because it contains no ptyalin to digest starch.

The carbohydrases of pancreatic and intestinal juices digest carbohydrates in the small intestine. The pancreatic juice contains a starch-digesting enzyme, called PANCREATIC AMYLASE. Starch is hydrolysed by it to maltose, isomaltose and 'limit' dextrins. Enzymes, isomaltase and maltase of the intestinal juices further hydrolyse maltose, isomaltose and 'limit' dextrins into glucose.

The animal polysaccharide glycogen present in the liver and flesh may also be similarly hydrolysed by the same enzymes into glucose. But ordinarily very little glycogen can be utilised from food, because glycogen is rapidly degraded to lactic acid by the enzymes of the liver and muscles after an animal is killed.

Besides MALTASE which hydrolyses maltose, the intestinal juice contains at least two other enzymes. SUCRASE hydrolyses sucrose into glucose and fructose and LACTASE breaks down lactose into glucose and galactose.

The human being is the only mammal who ingests significant amounts of lactose in milk even as an adult. Curiously, many human adults cannot digest milk, because with age they produce little or no lactase in the intestinal juice. In such persons, the lactose of milk remains undigested and is fermented in the intestine producing gases and acids. This results in flatulence, intestinal cramps and diarrhoea. But an intake of yoghurt (dahi) or curd (clotted casein) poses no digestive problem because lactose is fermented into lactic acid in yoghurt and is left in solution in the whey of curd. The digestibility of bread is increased by toasting because some of its starch is broken into dextrins during the process.

The cellulose of plant fibres is digested by microorganisms thriving in the alimentary canal of herbivorous mammals. Unlike vertebrates and most invertebrates, some bacteria and protozoans contain enzymes for digesting cellulose. Such microorganisms live as symbionts in the rumen and reticulum of ruminants like cows and buffaloes, and in the large intestine of other herbivores such as horses and donkeys. These microbes ferment cellulose into short-chain fatty acids such as acetic acid and propionic acid. These fatty acids are then absorbed and utilised by the host animal.

#### *Digestion of Proteins*

Food proteins are broken down ultimately into amino-acids by gastrointestinal enzymes. Enzymes hydrolysing proteins

In ruminants, cellulose fermentation is particularly facilitated by RUMINATION or chewing of the cud. Boluses of food are drawn from the rumen to the mouth, chewed thoroughly to break the plant fibres more finely, mixed with saliva to promote further fermentation and swallowed again into the rumen. There it undergoes further fermentation.

In rats, guineapigs and rabbits, fermentation and absorption of cellulose are not complete in a single passage of food through the intestine. So, they eat their faeces (COPROPHAGY or excreta eating) containing much undigested cellulose. This provides for the fermentation and absorption of the undigested cellulose again in the large intestine.

Microbial fermentation helps digestion of cellulose in the intestines of many invertebrates like termites. Some invertebrates themselves secrete cellulases for hydrolysing cellulose in the digestive tract.

are called PROTEASES or PEPTIDASES. Many of the proteases are secreted in inactive forms called proenzymes because if synthesised in active forms, they would hydrolyse cellular and extracellular proteins of the organism itself. Inactive proenzymes are activated at the sites of their actions either by specific proteases or by optimal pH changes. Saliva contains no protease and hydrolysis of proteins does not occur in the mouth. But if you eat an uncooked natural (native) protein such as that present in raw egg, unboiled milk or uncooked ger-

minating gram, salivary water denatures the protein without hydrolysing it.

Protein digestion starts in the stomach. The gastric juice of most vertebrates contains HCl and pepsinogen. HCl maintains a strongly acidic pH of about 1-2 in the stomach. At this acidic pH, inactive pepsinogen is spontaneously hydrolysed into active PEPSIN and an inactive peptide. Once some pepsin is formed it hydrolyses many other molecules of pepsinogen into pepsin in the same way. Pepsin hydrolyses proteins at an acidic pH; invertebrates do not have proteases for acting at an acidic pH in the alimentary tract. Therefore, protein digestion by pepsin-HCl, though almost universal in higher vertebrates, is absent in invertebrates. HCl not only provides an acidic pH in the stomach for optimum pepsin action, but also denatures many food proteins. This facilitates pepsin action. Pepsin hydrolyses many proteins into smaller molecules of peptones. It can digest even collagens of connective tissue fibres, but not keratins of horn, hair, skin or nail. As the food passes to the duodenum, pepsin action is stopped by the alkalinity of intestinal contents.

Digestion of the principal milk protein casein is initiated in the stomach with its coagulation. Pepsin hydrolyses soluble casein into paracasein and whey protein. Paracasein is then precipitated spontaneously as calcium paracaseinate to form the solid curd (COAGULATION OF MILK). Calf gastric juice contains another milk coagulating protease, called RENNIN. It is secreted as inactive pro-rennin. At the acidic gastric pH provided by HCl, pro-rennin is hydrolysed into active rennin. Rennin then hydrolyses casein into paracasein, leading to milk coagulation. Rennet tablets, containing rennin extracted from calf gastric mucosa, are

often used commercially for coagulating the casein of milk to curd. But adult cows or human infants do not secrete rennin. The function of rennin is taken over then by pepsin and other milk-coagulating enzymes. Coagulation of casein promotes its further digestion.

Pancreatic and intestinal juices contain a number of proteases. But most of the pancreatic proteases are secreted as inactive pro-enzymes, such as trypsinogen and chymotrypsinogen. In the intestinal lumen, pancreatic and intestinal juices mix together. Then a protease of intestinal juice, called ENTEROPEPTIDASE or ENTEROKINASE, initiates the coordinated activation of the pancreatic proteases. In fact, some of the inactive trypsinogen molecules of the pancreatic juice are first hydrolysed by enteropeptidase into an inactive peptide and active trypsin. Trypsin then hydrolyses the remaining trypsinogen molecules into trypsin. It also activates other pancreatic proteases, viz. chymotrypsin and carboxypeptidases. This enables the simultaneous action of all the pancreatic proteases for a very rapid digestion of proteins.

TRYPSIN acts best at an alkaline pH. This is provided in the small intestine by the bicarbonates of pancreatic and intestinal juices and bile. Trypsin hydrolyses proteins, particularly basic proteins, into peptides. But its action in digesting collagen is very limited. Trypsin is unable to hydrolyse casein for the coagulation of milk. So it cannot coagulate milk. But in predator animals drinking the blood of their prey, trypsin hydrolyses fibrinogen of blood into fibrin, leading to blood coagulation. Besides, trypsin activates the other pancreatic proteases. Trypsin cannot hydrolyse keratins.

Most vertebrates lack proteases for digesting some fibrous animal proteins such as hair keratin, silk fibroin and wool protein. Occasionally large balls of hair are found in the intestines of carnivores, causing great hindrance in the movement of food. Some invertebrates secrete enzymes for digesting such fibrous proteins. This is why some insects destroy silk fabrics and woollen garments.

CHYMOTRYPSIN is an important milk-coagulating enzyme. It hydrolyses casein into paracasein which then coagulates into calcium paracaseinate. But unlike pepsin and rennin, it acts in an alkaline medium. Chymotrypsin hydrolyses other proteins also into peptides. CARBOXYPEPTIDASES hydrolyse the terminal peptide bond of the peptide chain to release the last amino-acid from the peptide, thereby changing it into a smaller peptide.

The intestinal juice contains enteropeptidase, aminopeptidases and dipeptidases. The principal action of ENTEROPEPTIDASE (ENTEROKINASE) is to activate trypsinogen of the pancreatic juice. AMINOPEPTIDASES hydrolyse the terminal peptide bond of the peptide chain to release the last amino-acid from the peptide. So, both pancreatic carboxypeptidases and intestinal aminopeptidases progressively shorten a peptide into small peptides by releasing the terminal amino-acid at each step.

#### *Digestion of Fats*

LIPASES are enzymes for hydrolysing fats and oils. Lipases are soluble in water and are secreted in aqueous digestive juices.

But they are not soluble in fats and oils. On the contrary, fats and oils are insoluble in water. They form large immiscible droplets in aqueous media. Therefore, lipases can act only on the water-adjoining surfaces of fat droplets. Evidently, the larger the surface area of fat droplets, the greater is the action of the lipase on them. You are aware that the smaller the size of a droplet, the larger is its surface area relative to its mass. Thus, the lipase can digest fat in significant amounts only when large fat droplets are broken into tiny droplets to form a fine emulsion.

Fats are not digested in the mouth in higher animals because the saliva contains no lipase, nor is any fat-emulsifying agent present in the mouth normally. The stomach also lacks any fat-emulsifying agent. The gastric contents show only a mild lipase activity.

Fat is largely digested in the small intestine. The pancreatic juice contains a PANCREATIC LIPASE which is the principal enzyme for the digestion of fat. In addition, an INTESTINAL LIPASE occurs mainly in the intestinal epithelial cells and, to a smaller extent, in the intestinal juice. BILE SALTS are of prime importance in the digestion of fat. Bile salts are steroids secreted by the liver in the bile. In the intestinal lumen, they reduce the surface tension of fat droplets, causing their breakdown into many small ones. A stable fine emulsion of fat is thereby formed in the aqueous intestinal contents. This increases lipase action on fat.

The pancreatic lipase progressively hydrolyses triglyceride fats, first into diglycerides and then into monoglycerides, releasing a fatty acid at each step. About two-thirds of the food fat are usually digested to monoglycerides in this way. Some of the food fat is digested



only up to diglycerides while small amounts are absorbed as triglycerides into the intestinal cells. The intestinal lipase hydrolyses the absorbed diglycerides and triglycerides into fatty acids and monoglycerides. Fatty acids, monoglycerides and glycerol are the major end products of fat digestion.

### Absorption

Absorption is the process by which nutrient molecules are taken into the cells of a living organism. Most of the digested nutrients are absorbed in higher animals from the small intestine. You have learnt earlier that the presence of villi on the inner surface of the small intestine and the existence of microvilli on the free surface of the intestinal epithelial cells considerably enhance the absorptive capacity of the small intestine. Absorption across the plasma membrane of the intestinal cell depends on two types of processes, viz. physical processes such as diffusion and

osmosis, and energy-dependent active processes involving active participation of the cell.

### Passive Absorption

Nutrients may be absorbed passively by SIMPLE DIFFUSION. This requires the nutrient to be at higher concentration in the intestinal lumen than inside the cell. Its molecules should also be small and water-soluble. Diffusion of molecules would continue so long as the concentration difference persists. Thus diffusion cannot account for complete absorption of any nutrient from the intestine. Moreover, diffusion is a slow process. Water is absorbed by osmosis from the intestinal lumen to the intestinal cells and thence to blood as long as the solute concentration is higher in the blood than in the intestinal contents. Whenever any solute is absorbed from the intestine, its

Some nutrients such as fructose and mannose are absorbed from the intestine by FACILITATED DIFFUSION. This is also a passive physical process, not needing expenditure of energy or active cellular participation. Like simple diffusion, this process also depends on a higher concentration of the substance in the intestinal contents than in the intestinal cell or blood. So, facilitated diffusion cannot absorb a substance completely from the intestine. But the process is more rapid than simple diffusion because the substance is carried across the membrane in combination with some carrier molecule of the membrane.

If sea water is drunk, its  $Mg^{2+}$  ions increase the solute concentration in the intestinal lumen because  $Mg^{2+}$  is absorbed very slowly. The osmotic effect of  $Mg^{2+}$  in the intestinal lumen prevents water absorption from the intestine. On the contrary,  $Mg^{2+}$  draws water from the blood to the intestinal lumen by osmosis. So, water is not gained, but is lost from the blood on drinking sea water. In acute constipation purgatives containing magnesium salts (magnesium sulphate) are generally used. They increase the fluidity and volume of intestinal contents in the same way. This consequently stimulates intestinal peristalsis and evacuation of fluid faeces.

osmotic effect causes simultaneous absorption of an equivalent amount of water.

### Active Absorption

In this process, cells actively participate in absorbing a substance and have to perform work by spending energy. Active absorption occurs more rapidly than diffusion. If cells are poisoned with cyanide or depressed by cold, active absorption ceases and the rate of absorption declines. Active absorption can occur even when the concentration of a substance is much lower in the intestinal lumen than in the blood. By this process, a substance can be absorbed completely from the intestinal contents. Substances of high nutritional importance are usually absorbed actively from the small intestine, e.g.  $\text{Na}^+$ , glucose, galactose and amino-acids. Active absorption of  $\text{Na}^+$  is of considerable importance for the active absorption of glucose, galactose and amino-acids. Glucose and galactose are absorbed very rapidly and almost totally absorbed from the small intestine.

You should remember that during active absorption, the substrate is always carried across the membrane in a specific direction and never in the opposite direction, irrespective of its concentrations on the two sides. A substrate may be carried against its concentration gradient, the mechanism resembles a pump carrying water against gravity and has been called a pump by analogy. In a membrane pump each substrate is actively absorbed with the help of a specific membrane protein acting as its carrier. The energy required for this process is derived from the hydrolysis of ATP by the carrier protein acting as an ATPase. SODIUM PUMP of the mem-

brane helps in the active absorption of  $\text{Na}^+$  in the intestine. You have learnt it in Unit Two.

**Micelles in Fat Absorption:** Most of the end products of fat digestion are actively absorbed from the intestine. But unlike water-soluble sugars and amino-acids, monoglycerides, diglycerides and fatty acids are insoluble in water. So, they cannot be directly absorbed from the intestinal contents. They are first incorporated into small, spherical, water-soluble droplets called MICELLES with the help of the bile salts and phospholipids in the intestinal lumen. Each micelle is an aggregate of many molecules. It is from these micelles that fatty acids, glycerides, sterols and fat-soluble vitamins are absorbed into the intestinal cells. An obstruction in the bile duct may prevent the entry of bile into the small intestine (obstructive jaundice); in this condition, large amounts of unabsorbed fats are eliminated in the faeces. This emphasises the importance of bile in the absorption of fat. Normally, faeces contains almost no fat because the products of fat digestion are actively and almost totally absorbed.

Absorbed fatty acids, diglycerides and monoglycerides are used in synthesising fat in the intestinal cells. These fats are then released from the cells into the lymph in the form of droplets called CHYLOMICRONS. You will read about lymph in Chapter 35.

### Nutritional Requirements

#### *Nutritional Roles of Food Constituents*

You have learnt that the major constituents of food are carbohydrates, proteins and lipids. They are digested in the alimentary canal into small molecules such

as sugars, fatty acids and amino-acids. After absorption, some of these are oxidised for obtaining energy whereas others are used in synthesising large molecules of carbohydrates, proteins and fats, characteristic of particular species. Besides these three classes of organic materials, animals must also take in their foods small amounts of a wide variety of organic substances called VITAMINS. Many minerals must also be supplied in small amounts in the food. Some of these minerals such as sodium, potassium, calcium, magnesium, chlorine and phosphorus are required in larger amounts (MACROELEMENTS). Some others such as iron, iodine, zinc, manganese, cobalt, copper, molybdenum, selenium, fluorine, etc, are needed in very small amounts, hence they are called MICROELEMENTS or TRACE ELEMENTS. Minerals and vitamins occur in the form of small molecules and many of them need no digestion. But a few are absorbed with the help of some digestive juices like the bile and gastric juice. Each of these food constituents performs a distinct role in the body and is needed in specific amounts in the diet.

#### 4.2 Calorific Value

Carbohydrates: The principal nutritional role of carbohydrates is the production of energy. Complete combustion of 1 gram of carbohydrate in the bomb calorimeter in a laboratory yields 4.1 kcal. This is called the CALORIC VALUE of carbohydrate. But each gram of food carbohydrate yields 4 kcal of energy on oxidation in the body; this is called the PHYSIOLOGICAL FUEL VALUE of carbohydrates. Carbohydrates are more suitable for the production of energy in the body than proteins and fats, because carbohydrate molecules contain relatively more oxygen than the others and, consequently, require less

molecular oxygen for their oxidation. In other words, for each litre of oxygen consumed, carbohydrates yield far more energy than proteins or fats. Carbohydrates are supplied to the tissues mainly as blood sugar. In many animals, including mammals, glucose is the blood sugar. Food carbohydrates are the major source of the blood glucose. Carbohydrates are also stored in the tissues as glycogen for use in the production of energy, when necessary. Glycogen in the stored fuel particularly in such tissues as skeletal muscles which often have to work with a supply of oxygen far lower than their immediate need. You may explain this from the knowledge that carbohydrates use less oxygen than other foodstuffs for oxidation. Carbohydrates are catabolised into substances which may then be changed into amino-acids. Glucose is also used to synthesise some polysaccharides which enter into cellular tissue and structures.

For humans, 55-75 per cent of total food calories should be provided in the form of carbohydrates. Of these, 80-85 per cent should consist of easily digestible polysaccharides such as starch and dextrins, mostly from cereal grains, potatoes, cassava, etc. Athletes, labourers doing heavy work and mountaineers should live on high-carbohydrate diets because carbohydrates need less respiratory oxygen for their oxidation than other foods.

Proteins: The principal nutritional role of proteins is to build tissue structures. Amino-acids absorbed from food are used to synthesise structural proteins as well as numerous enzymes, carrier proteins, protein hormones and blood proteins. Therefore, proteins are essential for body growth, especially for the young. Their acute deficiency in food causes retardation.

tion of physical growth and mental abilities, failure of maintenance of body tissues, and anaemia. Nutritionally, amino-acids belong to two categories. Some of them cannot be synthesised in the animal body and must be supplied with food in adequate amounts. They are called ESSENTIAL AMINO-ACIDS. In contrast, other amino-acids may be synthesised in the body, particularly from carbohydrate metabolites. They need not be supplied in the diet and are called NON-ESSENTIAL AMINO-ACIDS.

Eight amino-acids are considered essential for human nutrition. These are methionine, threonine, tryptophan, valine, leucine, isoleucine, lysine and phenylalanine. Arginine and histidine are considered SEMI-INDISPENSABLE AMINO-ACIDS. Glycine, alanine, serine, cysteine, tyrosine, proline, aspartic acid and glutamic acid are some of the non-essential amino-acids.

Food proteins should include sufficient amounts of animal proteins such as milk, egg, fish and meat proteins, because they contain adequate amounts of all the essential amino-acids. Plant proteins like those of cereals and pulses are frequently deficient in one or more essential amino-acids. They are considered nutritionally inferior to animal proteins with respect to essential amino-acids. However, an intake of more than one plant protein in the same meal (e.g. sambar-rice, idli-sambar, dal-roti) improves the nutritional value of plant proteins, because the essential amino-acid deficient in each food is compensated by the same amino-acid in the other.

Besides forming proteins, dietary amino-acids are required for the formation of products like heme of hemoglobin, the hormones adrenaline and thyroxine, the skin pigment melanin, and purines and pyrimidines of nucleic acids. Some amino-acids give rise to carbohydrates in the body. Amino-acids are also catabolised to give energy. The caloric value and the physiological fuel value of each gram of protein amount to 5.65 and 4 kcal, respectively.

The protein requirement in the diet is higher when new tissues are being laid down for growth, development or repair; it rises during pregnancy and lactation, and is higher in infants and children. Inadequate intake of proteins may produce in children two deficiency diseases, Marasmus and Kwashiorkor. You will read about them later in this chapter.

**Fats:** A major nutritional role of fat is to serve as stored food for use in the production of energy. Fat has a caloric value of 9.45 kcal and a physiological fuel value of 9 kcal per gram. Because fat oxidation produces almost  $2\frac{1}{4}$  times the energy yielded by the same weight of glycogen, fat is more suitable as stored food. Surplus of dietary carbohydrates are converted largely into fats for storage. It is commonly known that lambs or pigs store large amounts of fat in their body when kept on starch-rich foods like gram, maize or cereals.

Fatty acids obtained from food fats are also used in synthesising structural lipids.

In man, 10-25 per cent of total calorie requirement should be supplied in the form of fats. But athletes, weight-lifters and manual labourers may take more than 40 per cent of their food calories in the

form of fats, because that will not raise the bulk of food but still fulfil the high calorie need. The ratio of saturated and unsaturated fats should be low because an excess intake of saturated fats like butter, clarified butter (ghee) and hydrogenated vegetable fats enhances blood cholesterol level.

Some polyunsaturated fatty acids (with more than one double bond) cannot be synthesised in the animal body and must be supplied with food to avoid their deficiency. They are called **ESSENTIAL FATTY ACIDS**. Linoleic, linolenic and arachidonic acids are essential fatty acids for man. They are constituents of structural lipids including membrane lipids. Food fats should be so chosen that they supply sufficient amounts of essential fatty acids equivalent to 3-6 per cent of total food calories. Essential fatty acids are present in many unsaturated vegetable oils such as groundnut oil, sunflower oil and safflower oil.

High amounts of fats, particularly saturated fats and cholesterol should be avoided by sedentary, old or obese persons and patients of heart disorders and high blood pressure.

**Energy Requirement:** Energy requirement of an individual is expressed as total calories to be obtained from the food every day. It is supplied by carbohydrates, proteins and lipids of the food. Energy requirement includes the requirement for growth, maintenance, vital activities (heart beat, respiration, urine formation, etc.), temperature regulation, reproduc-

tion and muscular activities. Total calorie requirement, therefore, depends on the age, sex and level of muscular work. It is higher per kg of body weight in a growing child and in an adult, lower in old people, higher in an adult man than in an adult woman and higher during pregnancy and lactation. Calorie requirement rises with the level of muscular work.

**Vitamins:** These are organic substances of various types. They have relatively small molecules. Vitamins cannot be synthesised in sufficient amounts by an animal and have to be supplied in its diet. A deficiency in the food of any of these vitamins produces deficiency symptoms. Some of the vitamins such as vitamin C and the B vitamins thiamin, riboflavin, nicotinamide, pyridoxine, biotin, pantothenic acid, folic acid and cobalamin are soluble in water and are called **WATER-SOLUBLE VITAMINS**. Other vitamins are not soluble in water, but dissolve in fats and fat-solvents like chloroform. These are called **FAT-SOLUBLE VITAMINS**. Vitamins A, D, E and K are such vitamins.

**Fat soluble Vitamins:** **VITAMIN A** or **RETINOL** is present in cod liver oil, shark liver oil, milk, butter and clarified butter (ghee). It is also synthesised in the body from plant pigments, called carotenes. Carotenes occur in yellow vegetables and crops like maize, carrot and papaya, and in green leafy vegetables like spinach. Vitamin A forms the retinal pigments, such as rhodopsin of rod cells and iodopsin of cone cells of the retina; these pigments enable a person to see. Vitamin A also maintains normal, living secretory epithelia in mucous membranes and glands and prevents keratin deposition.

**DAILY DIETARY REQUIREMENTS OF NUTRIENTS  
(RECOMMENDATION OF THE INDIAN COUNCIL OF MEDICAL RESEARCH)**

Individual	Total calories (kcal)	Proteins (g)	Calcium (g)	Iron (mg)	Vitamin A ( $\mu$ <sub>g</sub> retinol)	Thiamin (mg)	Riboflavin (mg)	Nicotinamide (mg)	Vitamin C (mg)	Folic acid ( $\mu$ <sub>g</sub> )	Vitamin B <sub>12</sub> ( $\mu$ <sub>g</sub> )	Vitamin D (IU)
<b>Men</b>												
Moderately active	2800	55	0.4-0.5	24	750	1.4	1.7	19	40	100	1	
<b>Women</b>												
(a) Moderately active	2200	45	0.4-0.5	32	750	1.1	1.3	15	40	100	1	
(b) Pregnant	2700	59	1.0	40	750	1.3	1.5	17	40	300	1.5	
(c) Lactating	2750	70	1.0	32	1150	1.4	1.6	19	80	150	1.5	
Boy (16-18 years)	2820	53	0.5-0.6	25	750	1.4	1.7	19	40	100	1	200
Girl (16-18 years)	2200	44	0.5-0.6	35	750	1.1	1.3	15	40	100	1	200

(keratinisation) in those epithelia. Its deficiency produces xerophthalmia and night-blindness.

VITAMIN D is synthesised in the skin from a cholesterol derivative by the ultra-violet rays of sunlight. It is also obtained from some foods such as cod liver oil, shark liver oil and eggs. It increases intestinal absorption of calcium and phosphorus, their retention in the body and their deposition in bones. Its deficiency produces rickets in children and osteomalacia in adults.

VITAMIN E inhibits peroxide formation and thereby prevents damage of membrane lipids. It thus maintains normal membrane structure. Its deficiency causes reproductive failure and degeneration of muscles in many mammals, and increases fragility of erythrocytes in man. Vitamin E occurs in vegetable oils.

VITAMIN K is obtained from green leafy vegetables like spinach, coriander leaves and radish tops. Vitamin K is also synthesised by bacteria in our colon and absorbed from there. This vitamin helps in the formation of prothrombin, an important factor for blood coagulation. Therefore, vitamin K helps in blood coagulation. Its deficiency may cause profuse and prolonged bleeding.

Water Soluble Vitamins: VITAMIN C or ASCORBIC ACID, is obtained from sour fruits like lemon and orange. It helps in the formation and maintenance of collagen in the intercellular material of connective tissues. Its deficiency produces scurvy in man.

VITAMIN B<sub>1</sub> or THIAMIN is present in

yeast, cereal grains, pulses, nuts, liver and meat. It forms one of the coenzymes for the aerobic metabolism of carbohydrates. The same coenzyme is also needed for pentose synthesis and metabolism. Thiamin deficiency produces beriberi in man.

VITAMIN B<sub>2</sub> or RIBOFLAVIN occurs in yeast, liver, milk, yoghurt (dahi), pulses and green leafy vegetables. It maintains normal healthy skin and oral mucosa. It forms two derivatives, FMN and FAD, which are coenzymes for some oxidising enzymes, called dehydrogenases (see Unit Two). Deficiency of riboflavin produces inflammation of the tongue, fissures in the lips and skin diseases.

NICOTINAMIDE is present in yeast, liver, cereal grains and pulses. It can be synthesised in the body from the amino-acid tryptophan. It forms two coenzymes NAD<sup>+</sup> and NADP<sup>+</sup>. These are coenzymes for a large number of dehydrogenases. Nicotinamide deficiency produces pellagra.

VITAMIN B<sub>6</sub> or PYRIDOXINE occurs in yeast, liver, cereals and eggs. Its deficiency produces convulsions and anaemia. Vitamin B<sub>6</sub> forms a coenzyme for many enzymes which participate in amino-acid metabolism.

BIOTIN is present in yeast, liver, eggs and pulses. It is the prosthetic group of some carboxylases. Avidin, a protein of raw egg white, inhibits intestinal absorption of biotin. Biotin deficiency may produce skin diseases, growth failure and loss of muscular control.

FOLIC ACID is obtained from green leafy

vegetables, liver and yeast. It forms a coenzyme which helps in DNA synthesis and maturation of erythrocytes. Its deficiency produces megaloblastic anaemia and gastrointestinal diseases. Some folic acid is synthesised by bacteria in colon and absorbed from there.

VITAMIN B<sub>12</sub> or COBALAMIN is a cobalt-containing vitamin. It is present in animal proteins such as meat, liver and fish. It is also synthesised in human colon and in the ruminant stomach of cattle. Intestinal absorption of cobalamin requires the action of a gastric enzyme, CASTLE'S INTRINSIC FACTOR. Failure of secretion of this enzyme produces vitamin B<sub>12</sub> deficiency, resulting in pernicious anaemia. Cobalamin promotes DNA synthesis, maturation of erythrocytes and myelin formation.

PANTOTHENIC ACID occurs in yeast, liver, eggs and pulses. It is also synthesised by bacteria in the colon. It forms coenzyme A which participates in the transfer and metabolism of fatty acid groups including acetyl group. Pantothenate deficiency produces gastrointestinal disorders, anaemia and reduced secretion of steroid hormones.

**Minerals:** Of the minerals required in the animal body, SODIUM and CHLORINE are obtained in sufficient amounts from table salts, pickles, and butter and many other foods.  $\text{Na}^+$  is the principal mineral cation in the extracellular fluid.  $\text{Cl}^-$  is the principal mineral anion in the ECF. POTASSIUM is obtained from many foods like molasses, banana, date and potato.  $\text{K}^+$  is the principal cation inside the cell.

Both ECF and cells, however, contain all three minerals.  $\text{Na}^+$  and  $\text{K}^+$  help to retain water in the ECF and the cell, respectively, and maintain the normal fluid balance between extracellular and intracellular fluids. They increase excitability of nerves and muscles. This helps in the conduction of nerve impulses.

CALCIUM and PHOSPHORUS are deposited in bones and teeth to give them strength and rigidity.  $\text{Ca}^{2+}$  is also essential for blood coagulation, neuromuscular function, cardiac function and actions of many enzymes and hormones. Phosphorus enters into many compounds such as nucleic acids and phospholipids, many coenzymes and high energy compounds like ATP. Phosphates help to maintain normal blood pH (buffer action). Calcium is obtained from foods such as milk, green leafy vegetables, carrot and small fishes. Phosphorus occurs in cereal grains, milk, eggs, fish and meat. Their dietary deficiency may produce rickets in children.

IRON is supplied by liver, pulses, green leafy vegetables, nuts and molasses. It is essentially required for hemoglobin synthesis. Cytochromes and many other oxidising enzymes contain iron in their molecules. Iron deficiency produces anaemia.

IODINE is used in the synthesis of thyroid hormones. It occurs in onion and marine fishes. Dietary deficiency of iodine reduces secretion of thyroid hormones and causes enlargement of the thyroid (iodine deficiency goitre). Iodised table salt is a good source of iodine for preventing such goitres.

### Nutritional Deficiencies and Imbalances

If a nutrient is not taken in adequate amounts for a long time, symptoms of



Of the other minerals,  $Mg^{2+}$ ,  $Mn^{2+}$ ,  $Mo^{6+}$  and selenium are required for the activities of different enzymes. Copper helps in the utilisation of iron. Therefore, copper deficiency may produce anaemia because of failure in iron utilisation.  $Zn^{2+}$  is a constituent of carbonic anhydrase and several other enzymes. Cobalt helps in erythropoiesis and in the activities of some enzymes. Fluorine maintains normal dental enamel and prevents dental caries.

deficiency of that nutrient appear in the organism. Such nutritional deficiencies affect the structure and function of those parts of the body which depend directly or indirectly on the nutrient.

Overnutrition or taking in a large amount of a particular nutrient is also harmful for the body. Intake of abnormally high amounts of even some vitamins such as vitamins D and A produces severe adverse symptoms. Some nutritional deficiencies and their symptoms are given in Table 33.2.

**BALANCED DIETS OF MODERATELY ACTIVE ADULT INDIANS  
(RECOMMENDED BY THE INDIAN COUNCIL OF MEDICAL RESEARCH)**

<i>Food</i>	<i>Recommended amounts (g per day)</i>	
	<i>Adult man</i>	<i>Adult woman</i>
Cereals (rice/wheat)	520	440
Pulses	50	45
Meat/Fish or Egg	30	30
Milk	1	1
Oil/fats	200	150
Sugar/molasses	45	25
Roots and tubers (potato, etc.)	35	20
Green leafy vegetables (spinach, etc.)	60	50
Other vegetables (cauliflower, etc.)	40	100
	70	40

Table 33.2

## NUTRITIONAL DISORDERS DUE TO DEFICIENCY OF DIETARY COMPONENT

<i>Name of the Deficiency</i>	<i>Deficient Nutrient</i>	<i>Symptoms</i>
Anaemia (microcytic)	Fe	No. and size of RBC and hemoglobin content reduced
Megaloblastic anaemia	<u>Folic acid and Vit. B<sub>12</sub></u>	Presence of large, immature, nucleated RBC in blood
Pernicious anaemia	Vit. B <sub>12</sub>	<u>Large, immature, nucleated RBC without hemoglobin.</u> This may be fatal unless treated with Vit. B <sub>12</sub> injections.
Xerophthalmia	Vit.A	Thickened, keratinised, opaque and ulcerated cornea. Prime cause of blindness in India, especially among children
Night-blindness	Vit.A	Less rhodopsin in rod cells of retina. So, no vision in dim light
Rickets (in children)	Vit.D	Weak, soft, thin bones due to poor deposition of Ca and P. Bent long bones and painful swellings on wrist, elbow and knee joints
Osteomalacia(adults)	Vit.D	Weak bones of vertebral column. Pelvis gets bent and deformed by body weight
Beriberi	Vit.B (Thiamin)	Reduces aerobic carbohydrate metabolism. So, peripheral nerves <u>inflamm</u> , causing pain, numbness and weakness of limb muscles, <u>paralysis</u> . Fluid accumulation in tissues, oedema of hands and legs. Cardiac oedema
Scurvy	Vit.C	<u>Fragile blood vessels because of defective collagen fibres in their walls.</u> Bleeding of gums, falling of teeth, fragile bones. Wound healing delayed. Vit.C is recommended in serious injury
Bleeding disease	Vit.K	<u>Delayed blood clotting, so profuse bleeding</u>
Marasmus	Protein and calories	Growth and replacement of tissue proteins impaired; so, emaciated body with thin limbs and prominent ribs. Dry, thin and wrinkled skin, diarrhoea

<i>Name of the Deficiency</i>	<i>Deficient Nutrient</i>	<i>Symptoms</i>
Kwashiorkor	Protein	Wasting muscles, thin limbs. Retarded growth of body and brain. Oedema, Diarrhoea
Pellagra	Nicotinamide	Swollen lips, thick pigmented skin of hands and legs. Irritability

## NUTRITIONAL DISORDERS DUE TO OVERNUTRITION

<i>Name of disorder</i>	<i>Excess Nutrient</i>	<i>Symptoms</i>
Hypercholesterolemia	Saturated fats like butter, ghee, vegetable oils. Red meat, eggs	Abnormally high blood cholesterol which deposits on walls of blood vessels causing their stiffening, rise in BP. Cardiac disorder
Obesity	Excessive intake of food calories, especially food with little water as sugar, honey, ghee	Excessive accumulation of fat in tissues. High BP, proneness to diabetes and cardiac disorders. Regular exercise and green vegetable intake recommended

During the Second World War (1939-1945), many thousands of the prisoners of war (POW) were disabled or killed by beriberi in German and Japanese POW camps.

Sea-faring fishermen sometimes eat raw fish from their catch. They may suffer from paralysis due to vitamin B<sub>1</sub> deficiency, because raw fish muscle contains an enzyme which destroys thiamin. Cooked fish has no such effect, because heat destroys that enzyme.

All bleeding diseases are not due to the nutritional deficiency of vitamin K. For example, bleeding diseases, called hemophilias, are caused by the inherited incapacity to synthesise some coagulation factors such as antihemophilic globulin. Spoilt hay of sweet clover contains a substance called dicumarol. Dicumarol prevents the action of vitamin K. So, cattle fed with spoilt sweet clover may suffer from vitamin K deficiency and prolonged uncontrollable bleeding.

Before the role of vitamin C in preventing scurvy was discovered, scurvy was a frequent and dreaded malady for sailors. Fresh vegetables and sour fruits were rarely carried for consumption in the sailing vessels of those days. So, sailors were often affected with severe scurvy on long cruises. Gums became swollen and bled profusely. Teeth got loose in their sockets and began falling out. Bones fractured spontaneously. Bleeding spots appeared beneath the skin. Fatigue was overwhelming. Old scars of remote past encounters and fights reopened and bled again. The superstitious sailors saw the disease as a punishment inflicted by the wrathful sea-god Neptune for violating his forbidden territory. More than half of the sailors accompanying Vasco da Gama in his maiden voyage to India died of scurvy before reaching India. After vitamin C was discovered, sour fruits were carried in sea-going vessels. Scurvy dramatically disappeared since then from among sea-going sailors.

Scurvy is believed to have contributed to the tragic death of Captain Scott and his fellow expeditionists during their South Pole expedition. Sufficient amounts of sour fruits were not included in the provisions accompanying them. So, they suffered from scurvy. Intense symptoms of scurvy delayed their progress and ultimately prevented them from returning to safety before the winter. This led to their death in the polar continent.

#### PROTEIN-ENERGY MALNUTRITION

Dietary deficiencies of proteins and total food calories are widespread in many underdeveloped countries of South and South-east Asia, South America, and West and Central Africa. Protein-energy malnutrition (PEM) may affect large sections of the population during drought, famine and political turmoil. This happened in Bangladesh during the liberation war and in Ethiopia during the recent severe drought. PEM affects infants and children to produce Marasmus and Kwashiorkor.

MARASMUS is produced by a simultaneous deficiency of proteins and calories. It is found in infants less than a year in age, if mother's milk is replaced too early by other foods which are poor in both proteins and caloric value. This often happens if the mother has second pregnancy or childbirth when the older infant is still too young.

In Marasmus, protein deficiency impairs growth and replacement of tissue proteins; stored fats and tissue proteins are catabolised also for energy production. So, extreme emaciation of the body and thin-

ning of limbs results. Ribs become very prominent. The layer of fat beneath the skin disappears; the skin becomes dry, thin and wrinkled. Growth rate and body weight decline considerably. Even growth and development of brain and mental faculties are impaired. Intestinal mucosa and digestive glands atrophy; digestion and absorption of food fail and diarrhoea results. But hands, feet and other body parts do not show any fluid accumulation (oedema) and swelling.

KWASHIORKOR is produced by protein deficiency unaccompanied by calorie deficiency. It results from the replacement of mother's milk by a high calorie-low protein diet in a child more than one year in age. Like marasmus, Kwashiorkor shows wasting of muscles, thinning of limbs, failure of growth and brain development, and diarrhoea. But unlike marasmus, some fat is still left under the skin; moreover, extensive oedema and swelling of body parts are seen.

## SUMMARY

Animals thrive on heterotrophic nutrition which may be holozoic or saprozoic. Food is digested by enzymes, called hydrolases. Digestion may be extracellular or intracellular. Animals have evolved the alimentary canal with associated glands for extracellular digestion.

The alimentary system of prawn consists of the alimentary canal and the hepatopancreas. The alimentary canal is divided into the foregut, the midgut and the hindgut. It communicates with the exterior at its two ends through the mouth and the anus. The hepatopancreas serves the roles of pancreas, intestinal glands and liver of higher animals. It secretes digestive enzymes and stores absorbed nutrients.

The mammalian alimentary system starts from the mouth. The tongue helps in food ingestion and with the incisor, canine, premolar and molar teeth, helps also in chewing and mixing the food with saliva. Saliva, secreted by paired parotid, submaxillary and submandibular salivary glands, contains the starch-digesting enzyme, ptyalin. It also contains mucin for lubricating the food for swallowing.

The mouth communicates through the pharynx with the oesophagus which propels the swallowed food to the sac-like stomach by its muscle movements. The glands on the stomach wall secrete into the gastric lumen the gastric juice containing HCl and the protein-digesting enzymes, pepsin and rennin. The muscles on the stomach wall churn and propel the food to the small intestine. Ruminant animals, such as cattle, possess a four-chambered stomach. Microbial fermentation of cellulose is carried out in its first two chambers, rumen and reticulum. The third chamber, omasum, concentrates the food while the fourth chamber, abomasum, secretes HCl and pepsin.

The stomach opens into the long, coiled, tube-like small intestine consisting of duodenum, jejunum and ileum. The common bile duct opens into the duodenum,

draining into it the juices of pancreas and liver. Intestinal glands on the intestinal wall secrete the intestinal juice into the small intestine. The pancreatic juice from the pancreas as also the intestinal juice contain many digestive enzymes. The liver secretes bile containing bile salts and bile pigments. Bile salts help in fat digestion and absorption. The gall bladder temporarily stores the bile secreted by the liver and ejects it into the small intestine.

The small intestine opens into the large intestine consisting of caecum, colon and rectum. The large intestine temporarily stores the unabsorbed food remnants and voids them as faeces through the anus. But it secretes no enzyme. Microbial fermentation of cellulose takes place in the spacious large intestine of herbivores.

Digestion of carbohydrate starts in the mouth. Ptyalin of saliva hydrolyses starch into maltose, isomaltose and limit dextrins. Pancreatic amylase of pancreatic juice digests starch in the intestine to similar products. Isomaltase and maltase of intestinal juice hydrolyse those products into glucose. Sucrase of intestinal juice hydrolyses sucrose into glucose and fructose. Lactase of intestinal juice hydrolyses lactose into glucose and galactose. Cellulose is digested into short-chain fatty acids by microorganisms in the large intestine and in the ruminant stomach.

Digestion of protein starts in the stomach. Pepsin and HCl of the gastric juice digest proteins into peptones. Pepsin also coagulates milk by hydrolysing the milk protein casein into paracasein. Rennin of calf gastric juice similarly coagulates milk. Pepsin and rennin are activated by gastric HCl. Enteropeptidase of the intestinal juice activates trypsin of the pancreatic juice in the intestinal lumen. Trypsin then hydrolyses proteins into peptides and activates carboxypeptidases and chymotrypsin of the pancreatic juice. Chymotrypsin coagulates milk. Carboxypeptidases hydrolyse peptides into smaller peptides and free amino-acids. Aminopeptidases of the intestinal juice also hydrolyse peptides into smaller peptides and amino-acids.

Lipases of the pancreatic and intestinal juices hydrolyse triglyceride fats into monoglycerides and fatty acids. The bile salts of the bile help in lipase activity by emulsifying large fat droplets into small ones.

Absorption of the digested products takes place mainly from the small intestine. The absorptive capacity of the latter is enhanced by the presence of villi on its wall and of microvilli on its epithelium. Nutrients may be passively and slowly absorbed by diffusion so long as their concentrations are higher in the intestinal lumen than inside the intestinal cell. Water is passively absorbed by osmosis with the absorption of any solute. Cells may also actively absorb a nutrient by spending energy. This active absorption occurs more rapidly than diffusion and even when the concentration of the nutrient is much lower in the intestinal lumen than in the blood.  $\text{Na}^+$ , glucose, galactose and amino-acids are absorbed actively. Most of the end products of fat digestion are incorporated into water-soluble droplets, called micelles, with the help of bile salts in the intestinal lumen. They are then absorbed from these micelles into the intestinal cells. Absorbed fats are released in the lymph as chylomicron droplets.

Carbohydrates are mainly used to produce energy. The caloric value and the physiological fuel value of carbohydrates amount to, respectively, 4.1 and 4 kcal per gram. For each litre of oxygen consumed, carbohydrates yield far more energy than proteins or fats. Carbohydrates are supplied to the tissues as the blood sugar which is glucose in many animals. Glycogen formed from glucose is stored as fuel in muscles which often have to work with a supply of oxygen far lower than their immediate need. For humans, 55-75 per cent of total food calories should come from carbony-

drates. Athletes, labourers doing heavy work, and mountaineers should live on high carbohydrate diets.

Proteins serve mainly to build tissue structures and are essential for body growth. Some of the amino-acids cannot be synthesised in the animal body and must be supplied with food. These are called essential amino-acids. Many plant proteins are nutritionally inferior to animal proteins because of a deficiency of some essential amino-acids in them. Besides forming proteins, dietary amino-acids also form products like heme, adrenaline, thyroxine, melanin, purines and pyrimidines, and carbohydrates. They may also be catabolised to give energy. The caloric value and the physiological fuel value of each gram of protein amount, respectively, to 5.65 and 4 kcal. The dietary requirement of proteins rises during growth, development and tissue repair.

Fats serve mainly as stored fuel for energy production. Fats have caloric and physiological fuel values, respectively, of 9.45 and 9 kcal per gram. Fatty acids of food fats are also utilised for synthesising structural lipids. 10-25 per cent of total caloric requirement may be supplied as fat in normal humans. The ratio of saturated to unsaturated fats should be low to avoid any rise in blood cholesterol.

The total caloric requirement depends on the age, sex and level of muscular work. It rises during pregnancy and lactation, and with the level of muscular work.

Vitamin A is essential in diet because it forms retinal pigments like rhodopsin and maintains normal living secretory epithelia. Its deficiency produces xerophthalmia and night-blindness in adults. Vitamin D is synthesised in the skin by the ultraviolet rays of sunlight. It increases intestinal absorption of calcium and phosphorus and their deposition in bones. Its deficiency produces rickets in children and osteomalacia in adults. Vitamin K helps in blood coagulation by promoting prothrombin formation. Its deficiency produces prolonged bleedings.

Vitamin C helps in the formation and maintenance of collagen in connective tissue. Its deficiency produces scurvy. Vitamin B<sub>1</sub> or thiamin forms a coenzyme for aerobic metabolism of carbohydrates. Its deficiency produces beriberi. Vitamin B<sub>2</sub> or riboflavin forms two coenzymes, FMN and FAD, which assist some oxidising enzymes. It also maintains normal healthy skin and oral mucosa. Nicotinamide forms two coenzymes, NAD<sup>+</sup> and NADP<sup>+</sup> which are needed by many oxidising enzymes. Its deficiency produces pellagra. Folic acid forms a coenzyme which helps in DNA synthesis and maturation of erythrocytes. Its deficiency produces megaloblastic anaemia. Vitamin B<sub>12</sub> or cobalamin is absorbed from the intestine with the help of the gastric enzyme, Castle's intrinsic factor. Failure of the secretion of intrinsic factor produces B<sub>12</sub> deficiency, resulting in pernicious anaemia. Cobalamin promotes DNA synthesis, maturation of erythrocytes and myelin formation.

Na<sup>+</sup> and K<sup>+</sup> help to maintain the fluid balance and excitability of nerves and muscles. Calcium and phosphorus are deposited in bones and teeth. Phosphorus occurs in nucleic acids, phospholipids and ATP. Phosphates help to maintain the blood pH. Iron is essential for the synthesis of hemoglobin. Its deficiency produces anaemia. Iodine is essential for the synthesis of thyroid hormones; its deficiency produces goitre.

Excessive intake of saturated fats may raise the blood cholesterol level, leading to cardiac disorders and rise of blood pressure. Excess intake of food calories may produce obesity.

## QUESTIONS

- Write whether the following statements are true or false.
  - (a) Pancreatic amylase digests proteins to amino-acids. *F it digest carb only*
  - (b) Marasmus results from the dietary deficiency of proteins. *T*
  - (c)  $\text{Na}^+$  is absorbed in the intestine with the help of the sodium pump of the cell membrane. *T*
  - (d) Deficiency of folic acid produces scurvy. *F scurvy by vit C deficiency*
  - (e) Castle's intrinsic factor participates in blood coagulation.
  - (f) Enteropeptidase activates pepsinogen to pepsin. *F it activate trypsinogen*
  - (g) Trypsin coagulates the milk protein casein. *F*
  - (h) Essential amino-acids cannot be synthesised in human body. *F*
- Name the enzymes for protein digestion in the gastric, pancreatic and intestinal juices, the substrates they digest, and the products of their action.
- Match the items in Column I with those in Column II

### Column I

- (a) Rennin
- (b) Enteropeptidase
- (c) Vitamin A
- (d) Goitre
- (e) Bile salts
- (f) Intestinal juice
- (g) Ptyalin
- (h) Vitamin  $\text{B}_{12}$
- (i) Cellulose
- (j)  $\text{HCl}$

### Column II

- f* (i) Lactase
- g* (ii) Starch
- m* (iii) Pernicious anaemia
- b* (iv) Trypsin
- e* (v) Micelle
- a* (vi) Night-blindness
- c* (vii) Casein
- d* (viii) Iodine
- j* (ix) Pepsin
- x* (x) Rumen
- (xi) Pellagra

- Mark the odd one in each series:
  - (a) Pepsin; lipase; trypsin; rennin ✓
  - (b) Bile salts; bile pigments; gall bladder; gastric juice
  - (c) Marasmus; pellagra; scurvy; xerophthalmia
  - (d) Maltase; lactase; aminopeptidase; sucrase
  - (e) Iodine; thiamin; folic acid; riboflavin
- How are the following enzymes activated in the alimentary canal?
  - (a) Pepsin (b) Carboxypeptidase (c) Rennin (d) Trypsin (e) Chymotrypsin
- Name the enzymes of the pancreatic juice, the substrates they digest, and the products of their digestive action.
- Distinguish between:
  - (a) Holozoic nutrition and saprozoic nutrition. ✓
  - (b) Caloric value and physiological fuel value. ✓
  - (c) Sucrase and maltase. ✓
  - (d) Essential and non-essential amino-acids. ✓
  - (e) Diffusion and active absorption. ✓
  - (f) Lipases and peptidases. ✓
  - (g) Extracellular digestion and intracellular digestion. ✓
  - (h) Autotrophic nutrition and heterotrophic nutrition. ✓



8. Name the nutrients the deficiencies of which produce the following diseases:  
 (a) Kwashiorkor; (b) Scurvy; (c) Osteomalacia; (d) Xerophthalmia; (e) Marasmus; (f) Pernicious anaemia; (g) Pellagra; (h) Goitre; (i) Rickets; (j) Bleeding disease.
9. Write about the importance and requirement of proteins in food.
10. From Column B choose the factor involved in the physiological role of each item of Column A.

## Column A

- (a) Pepsin  
 (b) Rhodopsin  
 (c) Lipase  
 (d) Cobalamin  
 (e) Prothrombin  
 (f) Collagen

## Column B

- (i) Bile salts  
 (ii) Vitamin K  
 (iii) Vitamin C  
 (iv) HCl  
 (v) Vitamin A  
 (vi) Carboxypeptidase  
 (vii) Intrinsic factor

11. Mention the nutritional roles of the following in the human body.  
 (a) Iron (b) Iodine; (c) Vitamin D; (d) Phosphorus; (e) Vitamin K; (f) Carbohydrates (g) Thiamin; (h) Calcium; (i) Nicotinamide; (j) Vitamin A and (k) Proteins.
12. Describe the following processes in the body:  
 (a) Coagulation of milk in the alimentary canal.  
 (b) Digestion of fats in the intestine.  
 (c) Digestion of starch in the alimentary canal.  
 (d) The role of bile salts in the digestion and absorption of fats.  
 (e) Microbial digestion of cellulose in the herbivore alimentary canal.



## RESPIRATORY GAS EXCHANGE

OXIDATION of nutrients releases their bond energy for utilisation in the body. Such oxidations take place in steps. The released energy is temporarily stored as ATP. The high energy bonds of ATP are subsequently broken to use the energy for various activities.

In some lower organisms such as anaerobic bacteria and yeasts, nutrients are oxidised without using molecular oxygen. Such a process is called ANAEROBIC METABOLISM or FERMENTATION. For example, yeast derives energy by the anaerobic fermentation of glucose to ethanol; lactic acid bacteria ferment glucose and lactose to lactic acid. Anaerobic metabolism occurs even in some multicellular animals such as intestinal parasites and liver flukes living in environments with less oxygen.

In most animals, however, tissue oxidations are carried out by AEROBIC RESPIRATION. Cells utilise molecular oxygen for oxidising nutrients aerobically; carbon dioxide is produced as a result of such oxidation. An exchange of oxygen and carbon

dioxide occurs between the organism and the surrounding medium. But even in aerobically respiring animals, anaerobic metabolism takes place in certain tissues like skeletal muscles which do not immediately get as much oxygen as is necessary for their work. This is why fast muscles produce lactic acid anaerobically from glucose during vigorous movements. There are also some cells like mammalian erythrocytes which lack mitochondria for aerobic respiration; they can only carry out anaerobic metabolism. The lactic acid produced anaerobically in some tissues is subsequently collected from blood and at least a part of it is oxidised aerobically by other tissues such as liver and cardiac muscle.

Aerobic respiration is carried out in two phases. One is EXTERNAL RESPIRATION. This consists of uptake of oxygen from the surrounding gaseous or liquid medium and elimination of carbon dioxide into that surrounding medium. This takes place by diffusion across the body surface. The other phase is INTERNAL RES-

**PIRATION.** This involves three activities: (i) oxygen uptake by tissue cells, (ii) tissue oxidation by oxidising enzymes, and (iii) carbon dioxide elimination from tissue cells. Thus, aerobic respiration involves the exchange of respiratory gases at two places in multicellular animals—one between the body surface and surrounding medium, the other between the individual cells and the extracellular fluid around them.

You may recall a sharp contrast between photosynthesis and respiration. Photosynthesis is an anabolic process—it synthesises organic molecules, trapping the solar energy in their chemical bonds. Respiration is a catabolic process—it breaks organic molecules to release their bond energy.

#### Organs for Respiratory Exchange in Various Animals

Whether between cells and the extracellular fluid or between the animal and the surrounding medium, gases are exchanged by the physical process of diffusion. A gas diffuses across a membrane from the side where its partial pressure is higher, to the side where its partial pressure is lower. But its diffusion is independent of the partial pressure of any other gas mixed with it. Partial pressure of oxygen ( $P_{O_2}$ ) is higher in the air inside the lungs, than in the venous blood; so, oxygen diffuses from the air to the venous blood in the lung. But simultaneously, carbon dioxide diffuses in the opposite direction from the venous blood to the air in the lungs, because the partial pressure of carbon dioxide ( $P_{CO_2}$ ) is higher in the venous blood than in the air. The same principle applies also to gas exchanges between the blood of an aquatic animal and the surrounding water.

For efficient gas exchange, the membrane separating the body fluid from the surrounding medium should be extensive, thin, highly vascular and easily permeable to oxygen and carbon dioxide. To fulfil these requirements, complex respiratory systems have evolved in many multicellular organisms. Indeed, a major evolution-

In some marine annelids such as *Nereis*, respiratory gases are exchanged between blood and seawater mainly through the integument over appendages called parapodia (Fig. 34.1). These are hollow and highly vascular appendages on lateral sides of most body segments. The integument over parapodia is particularly thin and permeable to gases.



Fig. 34.1 Parapodium of *Nereis*

any change in vertebrates has been a progressive increase in the surface area of the membrane through which respiratory exchanges take place.

In unicellular organisms such as aerobic bacteria and protists (e.g. *Amoeba*), respiratory gases diffuse between the surrounding medium and the cell across the plasma membrane. Even in some multicellular animals such as *Hydra*, gases are exchanged by diffusion between individual cells and the surrounding water.

#### *Gas Exchanges through General Body Surface*

In earthworms and leeches, gaseous exchanges occur through the skin over the entire body surface (CUTANEOUS RESPIRATION). Their skin is thin, moist, easily permeable to gases and highly vascular; thus, it is very suitable for respiratory exchanges.

Even in toads and frogs, some cutaneous respiration takes place across their moist and highly vascular skin, particularly during hibernation. However, they mainly respire through the lungs and the moist mucous membrane of the buccal cavity.

#### **Respiratory Organs of Animals**

Insects cannot carry out gas exchanges through their body surface, because their integument is impermeable to minimise the loss of body water through it to the atmosphere. Instead, they have developed a complex system of air tubes called TRACHEAE to reach the air directly near the tissue cells (Fig. 34.2). Each trachea communicates with the exterior through openings (SPIRACLES) in the body wall. Tracheae are swollen at places to form AIR SACS. Each trachea branches into TRACHEOLES. Each tracheole branches extensively in the tissues and finally end in an opening

immersed in the body fluid of the tissue. Relaxation of abdominal muscles draws in air through spiracles, tracheae and tracheoles. This air enters the body fluid through terminal openings of tracheoles. It then diffuses through the body fluid to reach the cells. Contraction of abdominal muscles drives air out from the tracheal system through spiracles. This back-and-forth movement of air in the tracheal system renews the air for gaseous exchange with tissue cells. But the body fluid does not circulate to distribute the gases to cells; it merely serves as a stationary medium for diffusion. Thus in insects, the gaseous exchange takes place directly between the outer atmosphere and tissues through the tracheal system.

Aquatic animals like fishes, tadpoles, prawns respire in water. They utilise the oxygen dissolved in water and release carbon dioxide back into water. Water contains far less dissolved oxygen content than that of atmospheric air. So, to get the required volume of oxygen by diffusion, a large volume of water has to be constantly moved over their respiratory surfaces and for this lot of energy has to be spent. In such animals, water is moved in a single direction over the respiratory surface. GILLS are the respiratory organs of aquatic animals (Fig. 34.3). Each gill bears rows of comb-like, soft, thin GILL-FILAMENTS. Each gill-filament bears many flat, parallel, membrane-like GILL-LAMELLAE. Each gill-lamella carries many blood capillaries. Water, taken through the mouth, is made to flow from the pharynx in a single direction between the gill-lamellae. Blood flows in the capillaries of gill-lamellae in a direction opposite to the flow of water over the lamellar surfaces. This greatly helps in the gaseous exchanges across the lamellar membrane between the capillary blood and the flowing water.

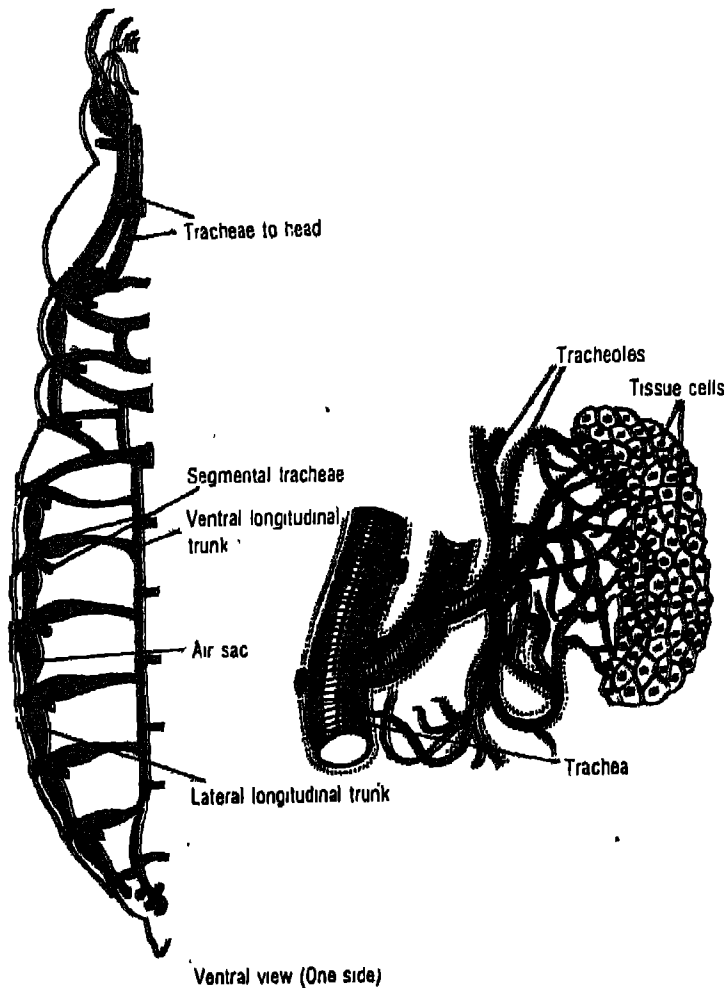


Fig. 34.2 Tracheal system of insect (Cockroach)

### *Mammalian Respiratory System*

Whether aquatic or terrestrial, all mammals use atmospheric air for respiration. Mammalian skin is impermeable so that water loss through it is minimised. But mammals need far more oxygen to maintain their high metabolic rates than lower

animals; so, they need a more extensive respiratory surface. A complex respiratory system has evolved in mammals to meet this need.

The mammalian respiratory system (Fig. 34.4) consists of the nasal cavity, nasopharynx, larynx, trachea, bronchi

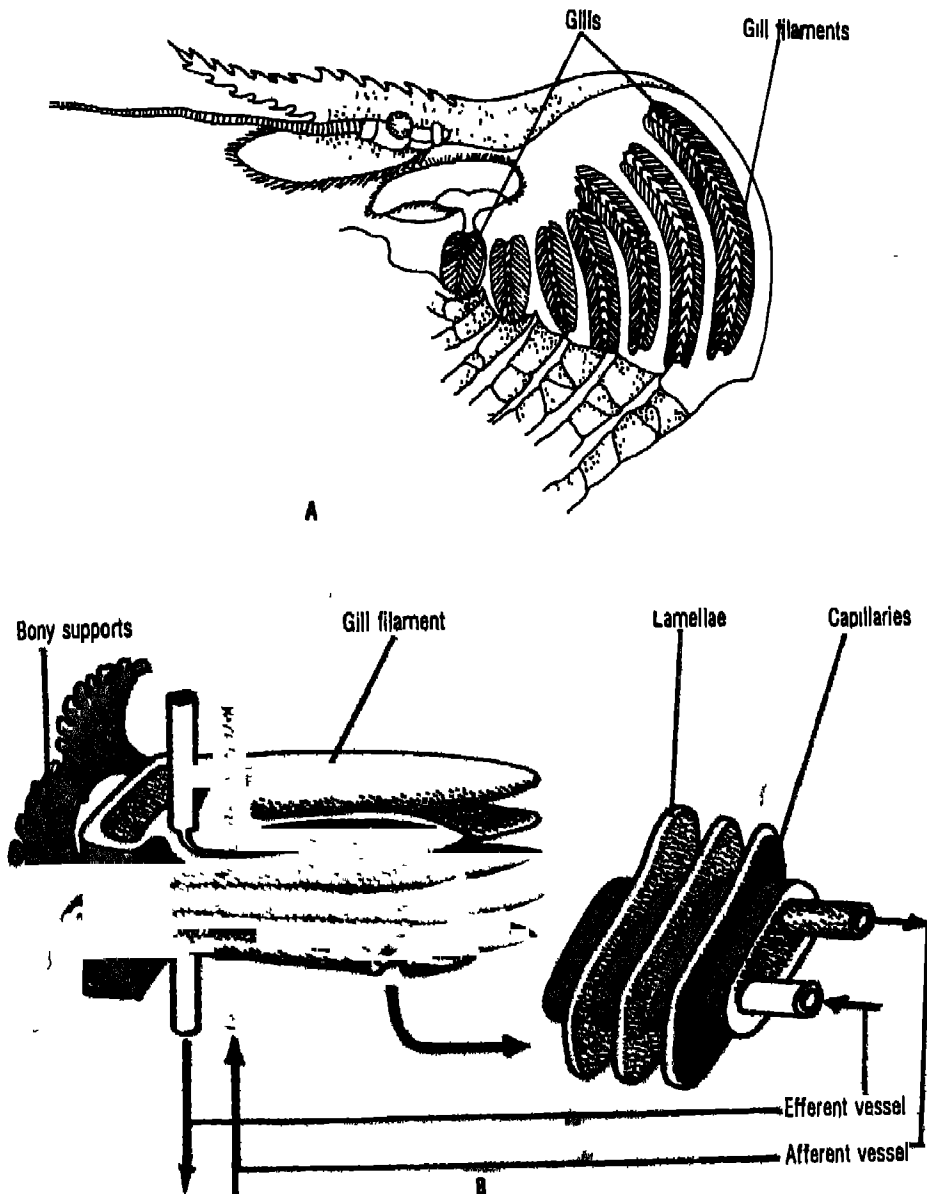
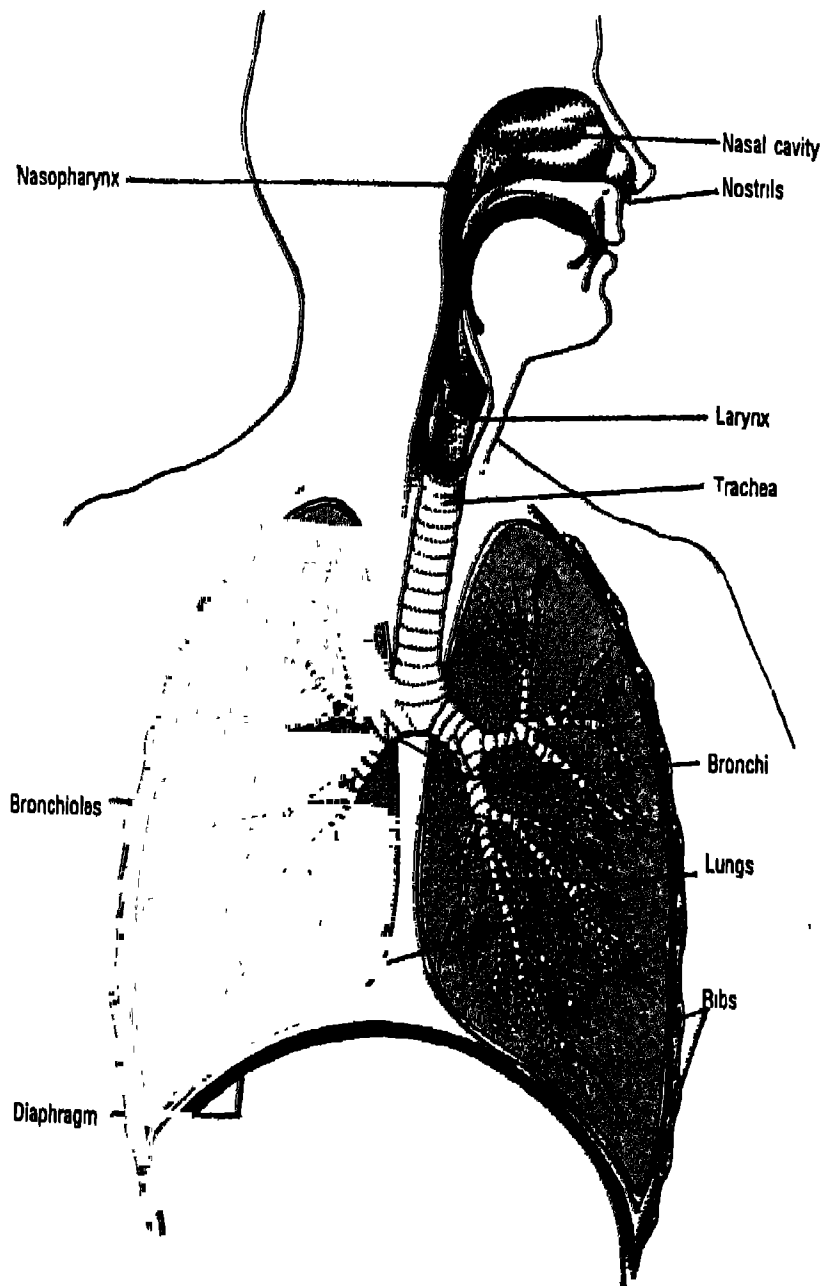


Fig. 34.3 Gills of aquatic animals  
 A. Prawn; B. Fish (diagrammatic)

bronchioles and lungs. It communicates with the exterior through the nasal openings. These lead to the nasal cavity, opening in the posterior part of pharynx called

the NASOPHARYNX which communicates through a cartilaginous structure called LARYNX with a long, wide cartilaginous tube called TRACHEA. The trachea runs



**Fig. 34.4** Respiratory system of mammal (human)

through the neck in front of the oesophagus, enters the thorax and divides into the

right and left **BRONCHI**. These two tubes enter into two elastic and conical lungs.



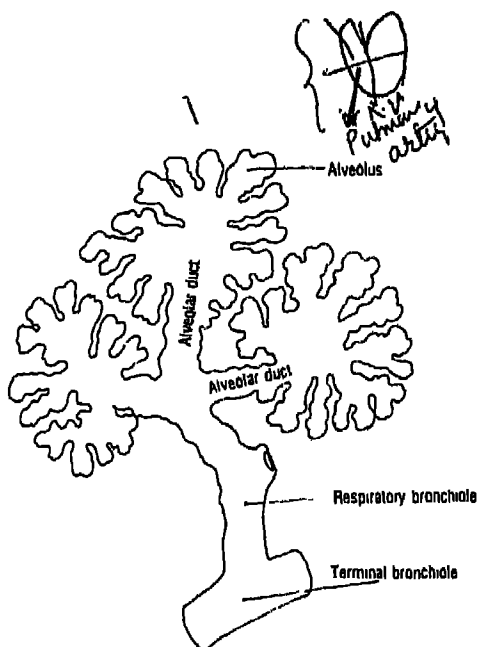


Fig. 34.5 Small air passages and alveoli inside the lungs (diagrammatic)

and divide repeatedly into small bronchi within the lungs. The lungs are enclosed in double-walled sacs called PLEURA. The bronchi branch repeatedly into smaller tubes called BRONCHIOLES. The smallest bronchioles open into many thin-walled sacs called ALVEOLI. Each alveolus is lined by a thin, highly permeable membranous wall surrounded by many blood capillaries. The lumen of alveolus is filled with air breathed in through nostrils. Branches of pulmonary artery supply blood to alveolar capillaries. This blood is poor in oxygen but rich in carbon dioxide. Respiratory gases are exchanged between the blood and the alveolar air by diffusion through the alveolar wall. The oxygenated blood is then returned from alveolar capillaries to pulmonary veins.

Alveoli are far more permeable and

vascular than the skin. The total alveolar surface, available for gas exchanges, far exceeds the general body surface. In adult man, the surface area of skin is around  $1.6 \text{ m}^2$  only, but the total alveolar surface area is nearly  $100 \text{ m}^2$ . So, lungs replace the skin very effectively in mammals as respiratory organs. Respiration by lungs is termed PULMONARY RESPIRATION.

There are some folds of mucous membrane stretching across the lumen of larynx. They are called VOCAL CORDS. They vibrate when air is blown through the larynx. This produces voice.

Reptiles, birds and adult amphibians, even aquatic amphibians like salamander respire through lungs. But bird's lungs are relatively non-elastic and are connected with elastic AIR SACS. Movements of air sacs help to direct air flow through lungs and enhance their ventilation with air.

#### *Mechanics of Pulmonary Respiration*

Respiration involves (i) letting in  $\text{O}_2$  from air into the lungs and  $\text{CO}_2$  out of the lungs by means of breathing movements (ventilation or breathing) (ii) exchange of gases on the alveolar surface, and (iii) transport and exchange of gases in the tissues. Lungs are located in the cavity of thorax. Lateral walls of thorax are mainly made of ribs and intercostal muscles attached to ribs. A muscular partition called the DIAPHRAGM separates the thoracic cavity from the abdominal cavity below. During INSPIRATION (breathing in), the diaphragm and some intercostal muscles contract, due to which the diaphragm moves down.

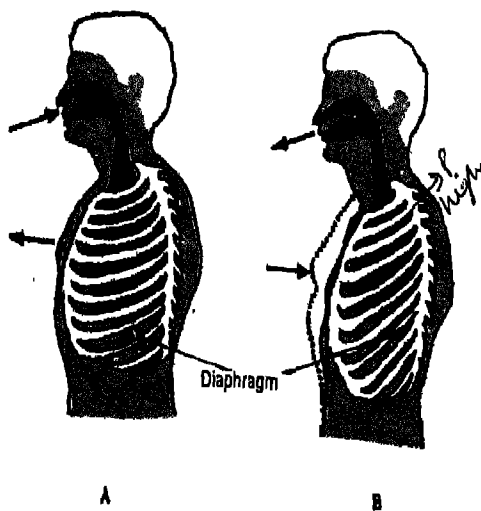


Fig. 34.6 Respiratory movements of thorax

A. during inspiration and B. during expiration

towards the abdomen while the intercostal muscles move the lateral thoracic walls outward and upward (Fig. 34.6). The volume of thorax increases. Because the thorax is a closed cavity, the pressure of air in it falls with the rise in its volume. Lungs being situated in the thorax, the fall of pressure in the latter lowers the pressure inside lungs a few mm Hg below the atmospheric pressure. Air from outside rushes into the lungs through nostrils, trachea and bronchi. Inspiration is thus brought about by contractions of the diaphragm and some intercostal muscles; these muscles are, therefore, called INSPIRATORY MUSCLES. But EXPIRATION (breathing out) is ordinarily carried out passively by relaxation of diaphragm and intercostal muscles. As they relax, the

diaphragm moves up towards the thorax while intercostals move the lateral thoracic walls inward and downward. The volume of thorax decreases and the pressure inside thorax and lungs is increased. This causes some air to be expelled from lungs to the atmosphere. This process of renewal of lung air by such muscular movements is called the mechanics of respiration.

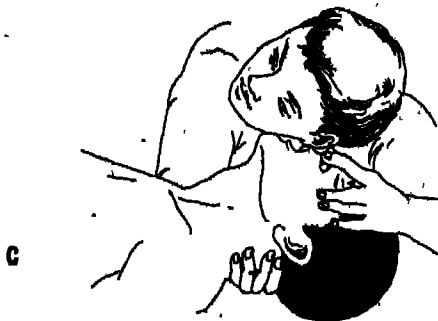
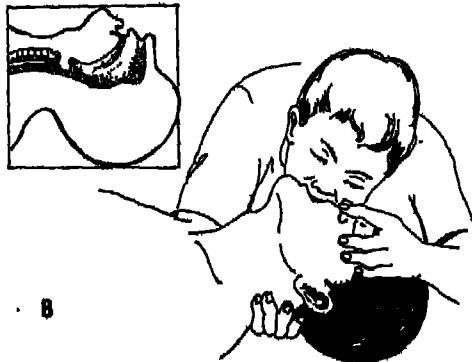
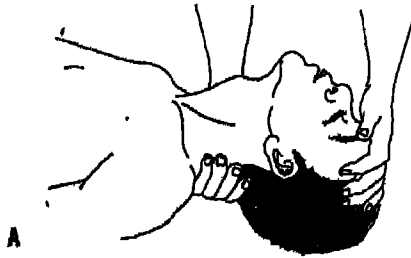
Each respiration consists of one inspiration and one expiration alternating with each other. The rate of respiration averages 12-14 per minute in a normal resting man. Alternate inspirations and expirations are due to the rhythmic arrival and interruption of nerve impulses to inspiratory muscles.

In **FORCEFUL EXPIRATION** requiring effort, a different group of intercostal muscles and some abdominal muscles contract to reduce the volume of thorax more than that in ordinary expiration. The consequent rise of pressure in the lungs exceeds that in ordinary expiration. So, a larger volume of air is breathed out. Such muscles are called EXPIRATORY MUSCLES.

With effort, a person can inspire 2-3 litres of air in excess of his tidal volume. This additional volume of air that can be breathed with maximum forceful inspiration, is called the INSPIRATORY RESERVE VOLUME (IRV). Similarly, after breathing out his tidal volume, he can expire an additional volume of about one litre of air by maximum effort. This additional volume is called the EXPIRATORY RESERVE VOLUME (ERV).

## ARTIFICIAL RESPIRATION

Breathing may stop as a result of drowning, electrocution or carbon monoxide poisoning. Artificial respiration is then tried for ventilation of the lungs.



In the MOUTH TO MOUTH BREATHING METHOD, the patient is made to lie on his back. The operator lifts and extends the patient's neck by placing a hand below it to open his airway. The operator then closes the patient's nostrils with fingers, applies his own mouth around the patient's mouth and blows about 1 litre of air into it to inflate the patient's lungs. Next, he releases the patient's mouth to allow expiration by the elastic recoil of his lungs. This procedure is repeated 10-15 times per minute.

### *Pulmonary Air Volumes*

TIDAL VOLUME (TV) is the volume of air breathed in and out during effortless respiration. It represents the volume of air renewed in the respiratory system during each respiration. It is about 500 ml in an adult person.

If a person first inspires with his utmost effort and then expires also with maximum effort, the volume of air breathed out is called the VITAL CAPACITY and it is about 3.5-4.5 litres in a normal adult person. It represents the maximum capacity of the individual to renew the air in his respiratory system. The vital capacity is higher in athletes than in non-athletes, in mountain dwellers than in people living on plains, in men than in women, and in youth than in old age. The higher the vital capacity, the greater the capacity for enhancing the ventilation of lungs to increase respiratory gas exchanges. Cigarette-smoking considerably lowers the vital capacity and consequently reduces the capacity for strenuous exercise or work. /

A person cannot expel all the air from his lungs even with maximum effort. Even after a maximum forceful expiration, about 1.5 litres of air are still left in the lungs and other parts of the respiratory system. This volume can never be driven out by respiration and is called the RESIDUAL VOLUME. Because the residual volume is always present in the lungs, gas exchanges continue there even at the end of maximum expiration or on holding the breath. In other words, although inspiration alternates with expiration, gaseous exchanges normally continue in lungs without interruption during both phases.

### *Pulmonary Exchange of Gases*

In mammals, external respiration takes places between the blood in alveolar capillaries and the alveolar air drawn from the atmospheric air. The atmospheric air contains about 21 per cent oxygen, 0.4 per cent carbon dioxide, 78.6 per cent nitrogen and small amounts of other gases and aqueous vapour. In the atmospheric air and consequently in the inspired air, partial pressures of oxygen ( $P_{O_2}$ ) and of carbon dioxide ( $P_{CO_2}$ ) are normally amount to 158 and 0.3 mm Hg, respectively, at the sea level. The lungs, into which the inspired air collects, contain some gases even at the end of expiration. But this air contains less oxygen and more carbon dioxide than the inspired air. Because the inspired air mixes with this air in alveoli the alveolar air comes to contain less oxygen and more carbon dioxide than the inspired air. When inspired air mixes with the already present alveolar air, the oxygen content and the  $P_{O_2}$  of the alveolar air increase to about 13.1 per cent and 100 mm Hg, respectively, while the carbon dioxide content and the  $P_{CO_2}$  of the alveolar air are about 5.3 per cent and 40 mm Hg, respectively.

The pulmonary artery contains venous (deoxygenated) blood which it brings to the alveolar capillaries supplying the alveoli. This blood has a  $P_{O_2}$  which is much lower than the alveolar  $P_{O_2}$ . So, oxygen diffuses from the alveolar air to the capillary blood. This oxygenated blood is collected from alveoli of the lungs by pulmonary veins. It has a  $P_{O_2}$  of about 95 mm Hg. At this  $P_{O_2}$ , arterial blood contains 19.8 per cent oxygen.

PARTIAL PRESSURES (mm Hg) OF RESPIRATORY GASES

Gas	Inspired air	Alveolar air	Venous blood	Arterial blood	Expired air
Oxygen	158	100	40	95	116
Carbon dioxide	0.3	40	46	40	32
Nitrogen	596	573	573	573	565

The mixed venous blood, reaching the alveolar capillaries, has a  $P_{CO_2}$  of 46 mm Hg which is higher than the alveolar  $P_{CO_2}$  of 40 mm Hg. So, carbon dioxide diffuses from the alveolar capillary blood to the alveolar air until the blood  $P_{CO_2}$  falls to 40 mm Hg. This lowers the carbon dioxide content of the blood from 52.7 per cent in the mixed venous blood to 49 per cent in the arterial blood. Thus the alveolar air gives up the oxygen received from the inspired air to the blood in pulmonary vein and pick up  $CO_2$  from the blood of pulmonary artery.

#### Gas Transport in Blood

**Oxygen Transport:** Very little of oxygen or carbon dioxide gets dissolved in the plasma to be carried in solution. Most of it is carried in chemical combinations in the erythrocytes (RBC) or in the plasma.

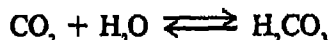
Of about 4.6 ml of oxygen entering each decilitre of blood in the lungs, only 0.17 ml remains in solution in the plasma. Oxygen diffuses into erythrocytes and combines loosely with the  $Fe^{2+}$  ions of hemoglobin to form oxyhemoglobin. Each of four  $Fe^{2+}$  ions in the hemoglobin molecule can bind with one molecule of

oxygen; so, oxyhemoglobin carries 1-4 molecules of oxygen according to its degree of saturation with oxygen. In the arterial blood hemoglobin is normally 97 per cent saturated with oxygen. The oxygenation of hemoglobin in the lungs depends on the arterial  $P_{O_2}$  and so, on the alveolar  $P_{O_2}$ . Moreover, the oxygen-affinity of hemoglobin is enhanced with the fall in the blood  $P_{CO_2}$  resulting from the elimination of carbon dioxide from the blood in the lungs. In the pulmonary alveoli, hemoglobin is exposed to high  $P_{O_2}$  and a low  $P_{CO_2}$ . The combined effects of these two factors enable hemoglobin to take up large volumes of oxygen in the lungs.

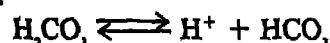
Oxyhemoglobin does not dissociate before blood reaches tissue capillaries. So blood carries its full load of oxygen until it enters the capillaries in the tissue. The more active the tissue, the lower is its  $P_{O_2}$  and the higher its  $P_{CO_2}$ . Both these factors combine to effect a dissociation of oxyhemoglobin to deoxyhemoglobin (reduced hemoglobin) and molecular oxygen. The  $P_{O_2}$  is much lower and the  $P_{CO_2}$  is much higher in an active tissue than in a less active one. So, far more oxygen is released from oxyhemoglobin in a more active tis-

sue than in a less active one. Each decilitre of blood releases up to 4.6 ml. of oxygen in the tissues, 4.4 ml from oxyhemoglobin and 0.17 ml from the dissolved oxygen in the plasma.

*Carbon Dioxide Transport:* (Most of the carbon dioxide produced in a tissue enters the red blood cells by diffusion. More carbon dioxide enters the blood from a more active tissue than from a less active one. Each decilitre (100 ml) of blood receives an average 3.7 ml of carbon dioxide from tissues. Some carbon dioxide gets dissolved in the plasma and is carried in solution and the rest enters the erythrocytes by diffusion. About 70 per cent of the carbon dioxide, entering into the erythrocytes, reacts with water to form CARBONIC ACID:



This reaction is catalysed by a zinc-enzyme, called CARBONIC ANHYDRASE. In erythrocytes, carbonic acid forms bicarbonate:



Some of the bicarbonate ( $\text{HCO}_3^-$ ) is carried in erythrocytes while most of it comes out in the plasma to be carried by it. About 30 per cent of carbon dioxide, entering the erythrocytes, combines with the globin part of deoxyhemoglobin (reduced hemoglobin) to form CARBAMINOHEMOGLOBIN. Carbon dioxide is thus carried in the blood in three major forms: bicarbonates in plasma and erythrocytes, carbaminohemoglobin in erythrocytes, and small amounts of dissolved carbon dioxide in plasma. The entry of carbon dioxide into the blood

from tissues increases the  $\text{Pco}_2$  of the blood. Compared to the arterial  $\text{Pco}_2$  of 40 mm Hg, the mixed venous blood has a  $\text{Pco}_2$  of 46 mm Hg.

On reaching the lungs, blood is oxygenated. Oxyhemoglobin is a stronger acid than deoxyhemoglobin. So it donates  $\text{H}^+$  which joins bicarbonate ( $\text{HCO}_3^-$ ) to form carbonic acid. The latter is cleaved into water and carbon dioxide by carbonic anhydrase. Thus, carbon dioxide is released from bicarbonate. Oxygenation of hemoglobin simultaneously releases carbon dioxide from carbamino-hemoglobin also, because oxyhemoglobin cannot hold as much carbon dioxide as deoxyhemoglobin. In this way, every decilitre of blood releases in the lungs about 3.7 ml of carbon dioxide. This  $\text{CO}_2$  is removed from the lungs during expiration.

#### *Gas Exchange in Tissues*

As in the lungs so also in the tissues, gases are exchanged by diffusion. Tissue cells use up oxygen during their activities. So, in the tissue fluid around the cells,  $\text{Po}_2$  falls below the arterial  $\text{Po}_2$ . Consequently, oxygen is released from oxyhemoglobin and diffuses from the capillary blood to the tissue fluid and thence, to the cells of the tissue. Carbon dioxide diffuses from the cells to the tissue fluid to raise its  $\text{Pco}_2$  above the arterial  $\text{Pco}_2$ . This enables carbon dioxide to diffuse from the tissue fluid to the capillary blood. Unlike the blood, tissue fluids do not carry these gases in chemical combinations such as oxyhemoglobin, carbaminohemoglobin or bicarbonate. Only small amounts of the gases are held in solution in the tissue fluid while most of them diffuse as such through it.

### MOUNTAIN SICKNESS

When a person living on plains ascends and stays on a mountain above 8000 ft from sea level, he develops certain symptoms in 8-24 hours. These symptoms include breathlessness, headache, dizziness, irritability, nausea, vomiting, mental fatigue and a bluish tinge on the skin, nails and lips. This is known as MOUNTAIN SICKNESS.

You know that the barometric pressure falls progressively with the rise in altitude. Simultaneously,  $P_{O_2}$  falls proportionately in the atmospheric air. This lowers the alveolar  $P_{O_2}$  and consequently reduces the diffusion of oxygen from the alveolar air to the blood. So, oxygenation of blood is decreased progressively with the rise in altitude. The fall in oxygenation of blood produces the symptoms of mountain sickness.

All tissues are not equally affected by the shortage of oxygen. The more active a tissue, the more it is affected. So, skeletal muscles, heart and brain are much more affected than skin, intestine and bones.

bin available for oxygen transport is reduced. The resulting deficiency of oxygen causes headache, dizziness, nausea and even death.

### CARBON MONOXIDE POISONING

If a person sleeps in a closed room with a lamp burning, the absence of sufficient amount of oxygen causes an incomplete combustion of carbon and produces carbon monoxide in the room. As the person inhales carbon monoxides, it diffuses from the alveolar air to the blood and binds to hemoglobin forming carboxyhemoglobin. The latter is a relatively stable compound and cannot bind any oxygen. So, the amount of hemoglo-

Cigarette-smoking leads to the disease EMPHYSEMA. In this disease terminal bronchioles get obstructed.

This reduces the ventilation of alveoli connected to them. Many alveoli coalesce together to form large chambers due to destruction of their walls. This change of smaller alveoli to large chambers reduces the area of alveolar surface across which respiratory gases are exchanged. All these changes seriously reduce both oxygen uptake and carbon dioxide elimination. Years of smoking may aggravate the condition and may suffocate the patient to death.

The pressure of water rises progressively with the depth in the sea. When a diver descends to great depths, his body is subjected to high pressure by the surrounding sea water. This tends to collapse his lungs unless he breathes compressed air under high pressure. But breathing of air at high pressure increases the partial pressures of gases in alveoli. As nitrogen forms about 79 per cent of the air, the rise in alveolar nitrogen tension affects the body most. While at the depth, much nitrogen diffuses and dissolves in the blood and body fats. This makes the diver lose his strength and work capacity, and feel drowsy. But more severe symptoms develop if he is lifted rapidly to sea surface (DECOMPRESSION SICKNESS). With the rapid fall in pressure, nitrogen is evolved from his body fluids and forms gas bubbles in the blood and tissues. Nitrogen bubbles may block pulmonary vessels producing serious shortness of breath. Itchings and local pain result from bubbles in peripheral nerves. Dizziness, paralysis and mental derangement may be caused by bubbles in the vessels of brain and spinal cord. To avoid decompression sickness, the diver should be lifted very slowly to the sea surface, nitrogen will then be evolved very slowly and will be effectively removed without forming bubbles.

## SUMMARY

Anaerobic bacteria and yeasts carry out anaerobic metabolism without using molecular oxygen. Most animals respire aerobically utilising molecular oxygen for oxidations of nutrients and produce carbon dioxide as a result. In aerobic respiration, external respiration consists of an exchange of oxygen and carbon dioxide between the surrounding medium and the organism across its body surface while internal respiration comprises the utilisation of oxygen, the carrying out of oxidations and the elimination of carbon dioxide by the cells of the organism.

In *Hydra*, respiratory gases are exchanged directly between the individual cells of the body and the surrounding aqueous medium. In earthworms and leeches and to some extent, in toads and frogs, gaseous exchange take place through the skin over the entire body surface (cutaneous respiration). In insects, air flows from the atmosphere to the tissues through air tubes called tracheae and diffuses from the open ends of tracheae to the cells.

Animals such as fishes and prawns possess gills as respiratory organs; gases are exchanged between the surrounding aqueous medium and the blood in gill capillaries. In mammals, lungs are the respiratory organs (pulmonary respiration). Lungs communicate with the atmospheric air through nostrils, pharynx, larynx, trachea, bronchi and bronchioles. Air is breathed into thin-walled sacs or alveoli of lungs. Respiratory gases are exchanged between the alveolar air and the blood in alveolar



capillaries, Alveoli have a far larger surface area than the total skin surface and consequently provide far greater respiratory exchanges.

Lungs are located in the closed cavity of thorax. Contractions of the diaphragm and some of the intercostal muscles increase the volume of thorax and consequently lower the pressure in the thorax as well as the lungs. This causes air to enter the lungs from the atmosphere producing inspiration. Relaxation of these muscles reduces the volume of thorax and consequently increases the pressure in the thorax as well as in the lungs. So, some air is expelled from the lungs to the atmosphere, causing expiration. During forceful expiration, some abdominal muscles and a different group of intercostal muscles contract to reduce the volume of thorax further; this raises the pressure in the lungs to expel more air from it than in effortless breathing.

Tidal volume is the volume of air breathed in and out during an effortless respiration. Vital capacity is the volume of air breathed out by a maximum forceful expiration, following a maximum inspiration. It is higher in athletes than in non-athletes. Even after a maximum forceful expiration, some air remains in the lungs; its volume is called the residual volume. Because of the residual volume of air, gaseous exchanges continue in the lungs even after a forceful expiration.

Oxygen diffuses from the alveolar air to the alveolar capillary blood as the alveolar  $P_{O_2}$  is higher than the  $P_{O_2}$  of the venous blood. Carbon dioxide diffuses in the reverse direction because the venous  $P_{CO_2}$  exceeds the alveolar  $P_{CO_2}$ .

Very little oxygen or carbon dioxide is carried in solution in the blood plasma. Most of the oxygen entering the blood combines loosely with hemoglobin to form oxyhemoglobin and is thus transported in erythrocytes. The high  $P_{O_2}$  and the low  $P_{CO_2}$  in alveoli enable hemoglobin to take up large volumes of oxygen in the lungs. On reaching the tissue capillaries, oxyhemoglobin dissociates to release oxygen; the low  $P_{O_2}$  and the high  $P_{CO_2}$  in tissues enhance this release of oxygen.

Carbon dioxide enters the blood from the tissues. It is carried mainly as bicarbonates in plasma and erythrocytes, and partly as carbaminohemoglobin in erythrocytes. Carbon dioxide reacts with water to form carbonic acid with the help of carbonic anhydrase in erythrocytes; carbonic acid gives rise to bicarbonate, some of which comes out in the plasma. Carbaminohemoglobin is formed by the combination of carbon dioxide with deoxyhemoglobin. On reaching the lungs, oxygenation of blood causes release of carbon dioxide from both bicarbonate and carbaminohemoglobin. Carbon dioxide is released from the lungs into the atmosphere during expiration.

Oxygen diffuses out from the blood to the tissues because the tissue  $P_{O_2}$  is lower than the arterial  $P_{O_2}$ . Carbon dioxide diffuses into the blood from the tissues as the tissue  $P_{CO_2}$  is higher than the arterial  $P_{CO_2}$ .

## QUESTIONS

1. Match terms in Column A with those in Column B:

Column A

(a) Tracheoles

Column B

(i) Yeast

- |                           |                     |
|---------------------------|---------------------|
| (b) Lactic acid           | (ii) Inspiration    |
| (c) Carbonic anhydrase    | (iii) Fish          |
| (d) Fermentation          | (iv) Vital capacity |
| (e) Gill filaments        | (v) Fast muscle     |
| (f) Cutaneous respiration | (vi) Insect         |
| (g) Diaphragm             | (vii) Bicarbonate   |
|                           | (viii) Earthworm    |

2. Explain why the following things happen:

- Far more oxygen is released from oxyhemoglobin in a more active tissue than in a less active one.
- Oxygenation of blood promotes the release of carbon dioxide from the blood in the lungs.
- Oxygen leaves the blood from tissue capillaries, but carbon dioxide enters the blood in tissue capillaries.
- Erythrocytes can carry out anaerobic metabolism only.
- Gaseous exchanges continue in the lungs without interruption even during expiration.
- Contraction of inspiratory muscles causes inspiration while their relaxation causes expiration.
- Oxygen enters the blood from the alveolar air but carbon dioxide leaves the blood to enter the alveolar air.

3. Distinguish between :

- External respiration and internal respiration.
- Inspiratory muscles and expiratory muscles.
- Photosynthesis and respiration.
- Anaerobic metabolism and aerobic respiration.
- Tracheoles and bronchioles.
- Carbamino hemoglobin and oxyhemoglobin.
- Alveolar air and inspired air.

4. Give the average values of the following in normal adult humans:

- Residual volume, (b) Arterial  $P_{O_2}$ , (c) Tidal volume, (d) Alveolar  $P_{CO_2}$ , (e) Rate of resting respiration, (f) Arterial  $P_{CO_2}$ , (g) Vital capacity, (h) Venous  $P_{O_2}$ .

5. How is carbon dioxide taken up from tissues and transported to lungs?

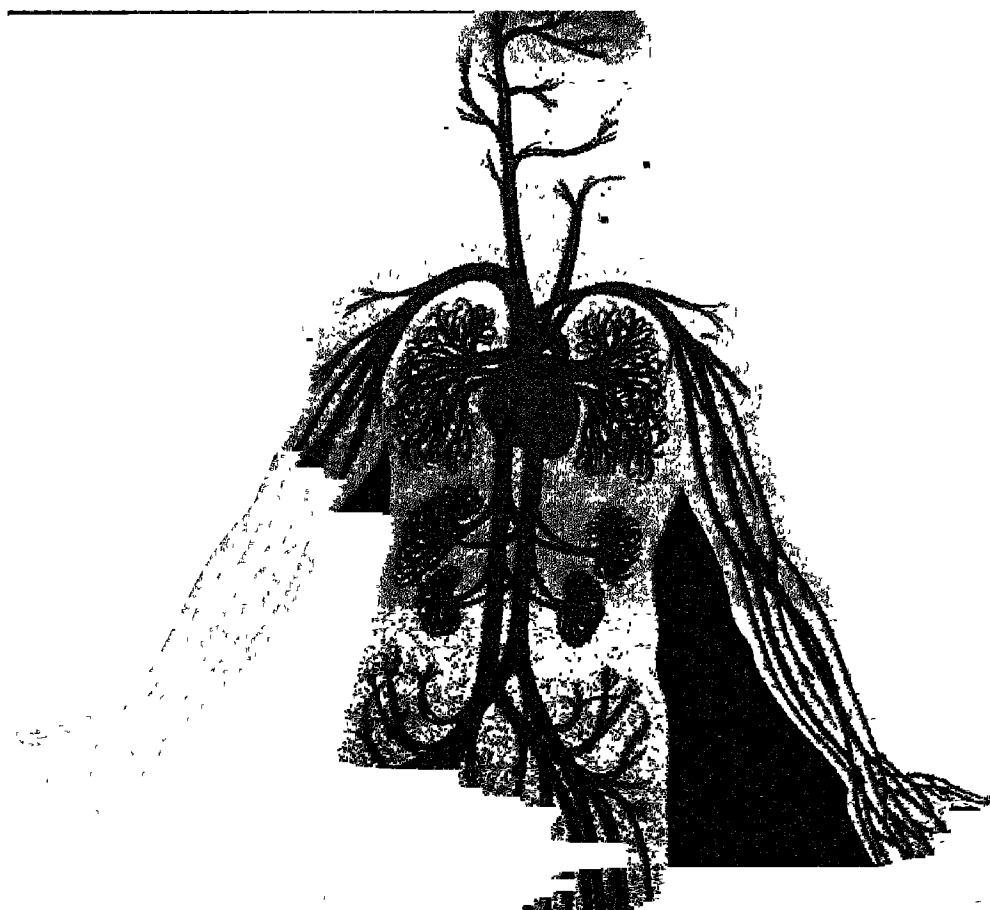
6. Fill in the blanks with correct words:

- Diaphragm contracts to help in \_\_\_\_\_ while the contraction of abdominal muscles help in \_\_\_\_\_.
- Vital capacity of trained athletes is \_\_\_\_\_ than that of non-athletes while the vital capacity of non-smokers is \_\_\_\_\_ than that of smokers.
- Leeches respire through \_\_\_\_\_ while prawns respire through \_\_\_\_\_.
- Alveolar  $P_{O_2}$  is \_\_\_\_\_ than the venous  $P_{O_2}$  while arterial  $P_{O_2}$  is \_\_\_\_\_ than the alveolar  $P_{O_2}$ .
- The volume of air left in the lungs after a maximum expiration is called \_\_\_\_\_ while the volume of air breathed out during a normal restful respiration is called \_\_\_\_\_.

7. Describe how the respiratory gases are exchanged between the blood and the alveolar air.

## RESPIRATORY GAS EXCHANGE

8. How is oxygen transported in the blood and released in the tissues?
9. State whether the following statements are true or false.
  - (a) Fishes respire through their skin.
  - (b) Aerobic respiration produces lactic acid at the end.
  - (c) Gas exchanges continue uninterrupted in the lungs by a forceful expiration.
  - (d) A person can expel all the air from the lungs by a forceful expiration.
  - (e) Expiration is normally brought about by the relaxation of inspiratory muscles.
  - (f) Vital capacity represents the maximum capacity to ventilate the lungs.
  - (g) A rise in  $P_{CO_2}$  increases the oxygen-affinity of hemoglobin.
  - (h) Forceful expiration results from a forceful contraction of diaphragm.
  - (i) Oxyhemoglobin can hold much less carbon dioxide in the form of carbaminohemoglobin than what deoxyhemoglobin can.
10. Describe how the contraction and relaxation of some skeletal muscles produce respiratory movements.



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## **CIRCULATION OF BODY FLUIDS**

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ALL parts of the body require nourishment and oxygen, and metabolic wastes need to be removed from the body. These and some other functions are carried out by an extracellular fluid which flows throughout the body. This flow is known as circulation and the organs concerned constitute the circulatory system.

### **Functions of the Circulatory system**

The circulatory system varies in different kinds of animals but its functions are the same. These functions are: (1) The circulating fluid **TRANSPORTS NUTRIENTS** from their sites of absorption to different tissues and organs for storage, oxidation or synthesis of tissue components. (2) It also **CARRIES WASTE PRODUCTS** of metabolism from different tissues to the organs meant for their excretion from the body. (3) It **TRANSPORTS RESPIRATORY GASES** between the respiratory organs and the tissues. Oxygen is thus carried from the respiratory organs to the tissues while carbon dioxide is carried from the tissues to the respiratory organs for its removal from

the body. (4) The circulating fluid **CARRIES METABOLIC INTERMEDIATES** from one tissue to another for their further metabolism; for example, blood carries lactic acid from muscles to the liver for its oxidation. (5) It also **TRANSPORTS INFORMATIONAL MOLECULES** such as hormones, from their sites of origin to the tissues which they stimulate or inhibit. (6) Water,  $H^+$ , chemical substances and heat are **UNIFORMLY DISTRIBUTED** all over the body by the circulating fluid.

### **Water Circulation System**

A body fluid circulates through a well developed circulatory system in the highest advanced animals. But lower animals such as sponges and *Hydra* lack a definitive circulatory system and use water from the surrounding medium as the circulatory fluid.

Sponges possess an extensive **CANAL SYSTEM** communicating with the exterior through a large number of minute pores in the body wall (Fig. 35.1). Water flows into the canals from the surrounding medium

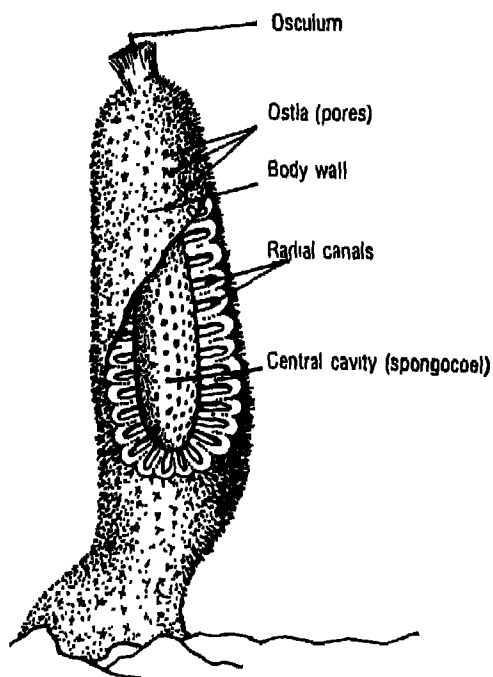


Fig. 35.1 Canal system in sponge (partially dissected to show inner organisation)

and it carries food and oxygen to the cells, takes away waste products and carbon dioxide from them and, finally, passes out of the body.

*Hydra* possesses a single, central, water-filled body cavity (coelenteron) which communicates with the surrounding aqueous medium through its mouth (Fig. 35.2). Water circulating in the coelenteron takes food and oxygen to the cells on the body wall and carries away waste products and carbon dioxide from the cells.

### Blood Vascular System

More advanced animals possess higher

metabolic rates. So, they need a greater and speedier supply of nutrients and oxygen to their tissues as also a rapid disposal of waste products and carbon dioxide. They have blood as the specialised circulatory fluid, and the circulatory system consists of the heart and the blood vessels for pumping and conducting blood to the tissues. In contrast to the water drawn from the surrounding aqueous medium, blood contains carrier molecules (e.g. hemoglobin and plasma proteins) for transporting much larger amounts of oxygen, carbon dioxide and nutrients. Moreover, the use of blood instead of external water as the circulating fluid minimises the possibility of harm due to unfavourable changes in the external medium. The organ-system comprising the heart and the blood vessels, constitutes the blood vascular system. The **HEART** serves as an automatic pump driving blood regularly and rapidly into the vessels. The blood vessels include arteries and veins. **ARTERIES** conduct the blood from the heart to other tissues; **VEINS** bring blood from other tissues to the heart. Higher invertebrates and all vertebrates possess the blood vascular system. The blood vascular system may be of two types, the open and the closed circulatory systems.

### Open Circulatory System

In many advanced invertebrates such as prawns, insects and molluscs, the blood does not remain confined to blood vessels, but flows through open spaces and channels called lacunae and sinuses in the tissues. The tissues are thus in direct contact with blood. A sufficiently high blood pressure, however, cannot be maintained in the open lacunae and sinuses in spite of the pumping action of the heart. So, blood flows at a very slow velocity in the lacunae

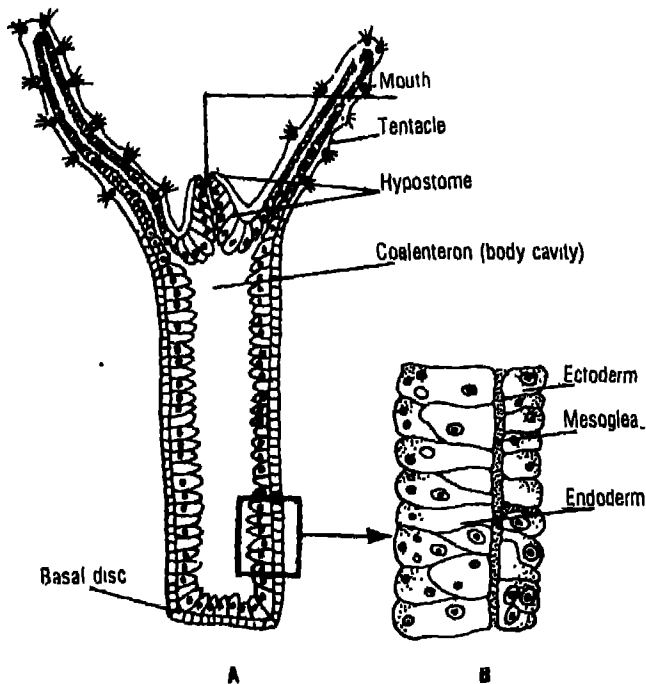
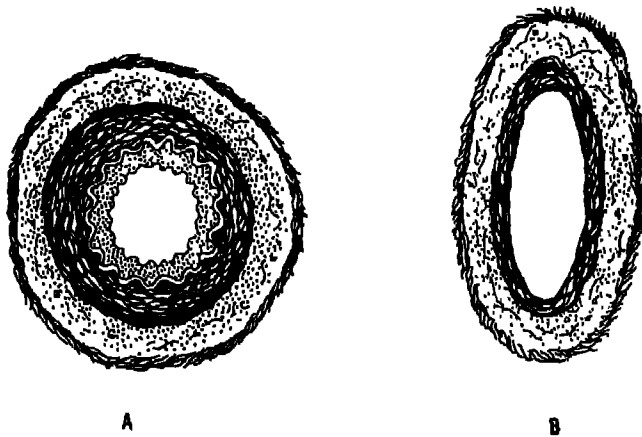


Fig.35.2 A. Longitudinal section of *Hydra* (diagrammatic); B. A portion of body wall (enlarged)

and sinuses. The oxygen-carrying pigments are usually dissolved in the plasma of the blood. For example, the heart of prawn pumps oxygenated blood into some arteries. These arteries directly open into lacunae and sinuses. Such spaces carrying blood are called HAEMOCOEL. Exchanges of respiratory gases, nutrients and waste products take place directly between the blood in those lacunae and sinuses and the surrounding tissues. The deoxygenated blood then passes through the gills of the animal for oxygenation. The oxygenated blood returns from the gill to a sinus surrounding the heart. From there, the blood enters the heart through slit-like openings in the cardiac wall. The prawn heart always contains oxygenated blood only.

#### *Closed Circulatory System*

The circulation of blood in the closed circulatory system was discovered and demonstrated for the first time by William Harvey (1578-1657). In vertebrates, the heart and the blood vessels form a closed system of chambers and tubes, having no direct communication with any open body cavity or space. The heart pumps the blood into arteries. Arteries possess thick walls with plenty of smooth muscles (Fig. 35.3). Larger arteries branch repeatedly into smaller arteries; these branch ultimately into small vessels called ARTERIOLES. Arterioles also have smooth muscles on their walls. Contraction and relaxation of these muscles alter the diameters of arterioles and thereby respectively reduce and increase the blood flow through them.



**Fig. 35.3** Transverse section of an artery (A) and a vein (B). Note the thick wall of artery in comparison to that of the vein.

This, in turn, regulates the volume of blood flowing through a tissue or organ according to its need. Arterioles divide in the tissues into many tiny, thin-walled vessels called **CAPILLARIES**. Their wall is made of a single layer of flat endothelial cells and is consequently very permeable to water and small solutes, but not to proteins and other macromolecules. Nutrients, respiratory gases, metabolites and informational molecules are exchanged between the blood and the surrounding tissues across the capillary wall. Capillaries unite into small vessels called **VENULES** which join each other to form bigger vessels, called **VEINS**. Veins return the blood ultimately to the heart. In contrast to the arterioles and arteries, venules and veins possess thinner and less muscular walls (Fig. 35.3). **VALVES** are present in the heart chambers, at the openings of the heart into large arteries and in the veins. They are made of two or three cup-shaped flaps or cusps attached to the vessel wall; they help to maintain the blood flow in a single direction in the closed circulatory system. These valves resemble swing doors in

action—when pushed by blood in the right direction, the flaps of the valve swing apart and allow the blood to flow through; but when pushed in the opposite direction, the flaps close sharply to block the passage through the valve.

The closed circulatory system considerably enhances the speed, precision and efficiency of circulation. Because the blood flows far more rapidly in closed blood vessels than in wide and open channels and body cavities, it takes much shorter time to circulate through the closed system and return to the heart. This quickens the supply and removal of materials to and from the tissues by the blood. You have learnt that in the closed system, the arteriolar diameter can be regulated to alter the blood flow, so, the volume of blood flowing through a tissue or organ may be regulated according to its needs by controlling the contractions and relaxations of the smooth muscles on its arterioles. No such regulation is possible in the open system where the blood flows in open lacunae and sinuses.



## THE HEART

The heart is a pumping organ of the blood vascular system. It is a hollow muscular organ, made of cardiac muscle fibres. The heart beats spontaneously and rhythmically throughout the life. It consists of chambers communicating with each other. The chamber which receives blood returned from other tissues is one or two **AURICLES (ATRIA)** and in some animals, a **SINUS VENOSUS**. The heart chambers pumping blood to different tissues consist of one or two **VENTRICLES**. The number of chambers varies in different animals because some chambers have been con-

densated together while others have been partitioned into separate chambers at various stages of evolution. Because the fish heart contains and pumps only deoxygenated blood it has a sinus venosus, a single auricle and a single ventricle—neither of which need to be partitioned into halves for separating deoxygenated and oxygenated blood. Amphibian and reptilian hearts pump both deoxygenated and oxygenated blood. So, the auricle is partitioned in them by a septum into a right auricle receiving only deoxygenated blood, and a left auricle receiving only oxygenated blood. But the ventricle is a

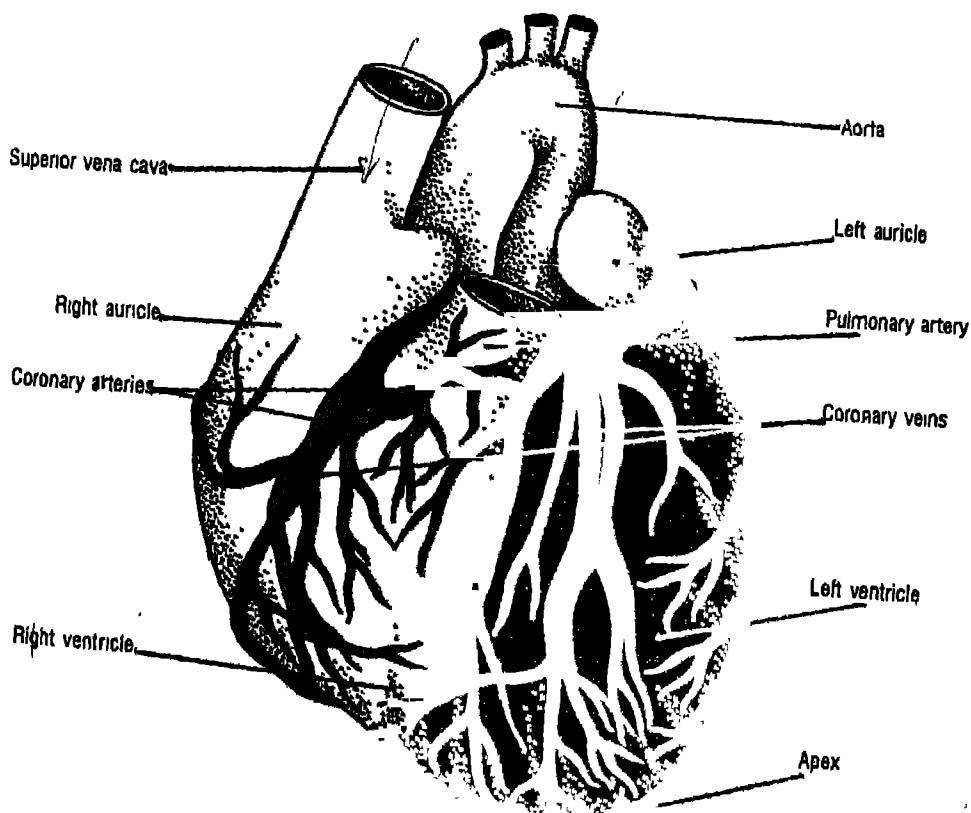


Fig. 35.4 External structure of the human heart

single unpartitioned chamber in amphibians while in reptiles, it is incompletely partitioned into two; in both cases, there is some mixing of deoxygenated and oxygenated blood in the ventricle. In mammals, the ventricle is completely partitioned into a right ventricle and left ventricle to prevent mixing of deoxygenated and oxygenated blood. Moreover, the sinus venosus, present, in fishes, amphibians and reptiles, has disappeared from the mammalian heart.

### Mammalian Heart

In mammals and birds, the sinus venosus has totally fused with the right auricle and does not form a separate chamber. The right and left halves of the heart are also completely partitioned off.

The human heart is situated in the

thorax between the lungs with its apex resting on the diaphragm. It is a hollow conical organ with its narrow apex directed downwards and to the left (Fig. 35.4). It measures about 12 cm in length and 9 cm in breadth and consists of four chambers, viz. two ATRIA (AURICLES) and two VENTRICLES. The large veins which return blood from most of the body tissues to the sinus venosus in lower vertebrates, open directly into the right atrium in mammals.

The great veins returning venous blood from upper and lower parts of the body and opening into the right atrium and are called superior and inferior VENAE CAVAE. The right and left atria are totally separated from each other by the INTERATRIAL SEPTUM (Fig 35.5). The left atrium receives oxygenated blood returned from

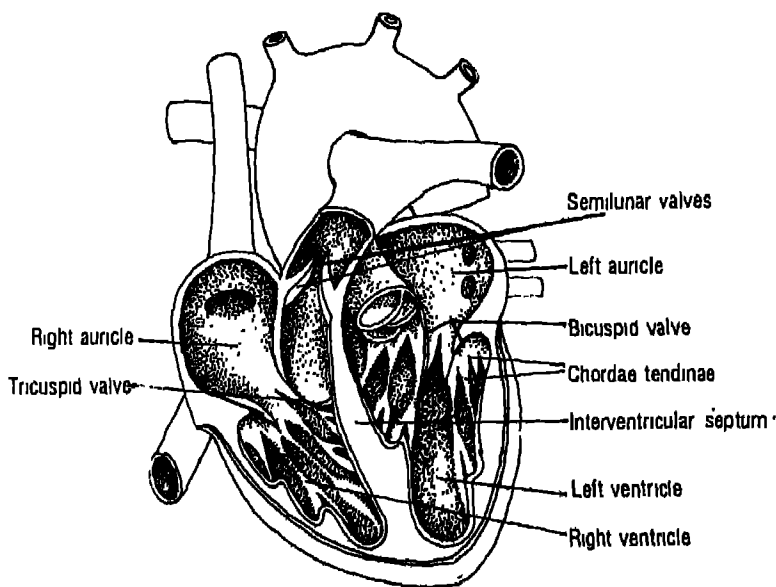


Fig. 35.5 Internal structure of human heart

the lungs by pulmonary veins. The two atria open into the respective ventricles, each opening being guarded by an ATRIO-VENTRICULAR VALVE or AV VALVE. The right AV valve is called the TRICUSPID VALVE (made of three flap-like cusps) while the left AV valve is known as the BICUSPID (made of two cusps) or MITRAL VALVE. The AV valves allow blood to flow from the atria to the respective ventricles, but prevent blood from flowing in the reverse direction.

The VENTRICLES have far thicker muscular walls than the atria. The right ventricle receives deoxygenated blood from the right atrium. It has a wall thinner than that of the left ventricle which receives oxygenated blood from the left atrium. This is because the right ventricle needs to pump deoxygenated blood to the nearby lungs only while the left ventricle is required to pump oxygenated blood all over the body. The two ventricles are totally separated from each other by a complete INTERVENTRICULAR SEPTUM. So, there is no mixing of deoxygenated and oxygenated blood in the ventricle. The right ventricle opens into the pulmonary artery going to the lungs; the left ventricle opens into the aorta supplying blood to all other tissues and organs. SEMILUNAR VALVES guard the openings of these great arteries in the ventricles; each semilunar valve is made up of three semilunar cusps and allows blood to enter the great artery from the ventricle, but prevents blood flow in the reverse direction.

#### *Course of Circulation through Mammalian Heart*

During each heart beat, the chambers of the heart contract and relax in a specific sequence. The contraction and the relaxation of a cardiac chamber are respectively

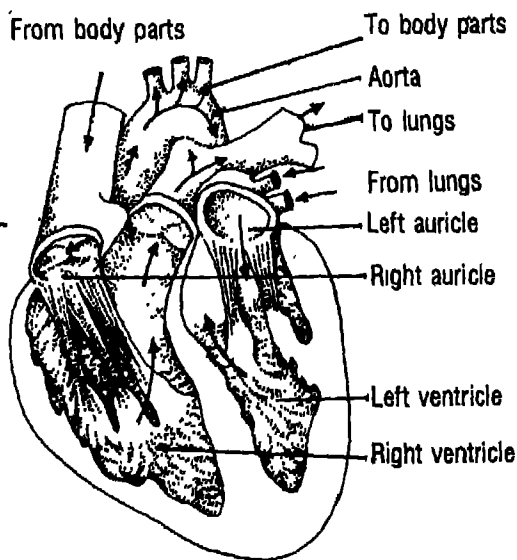


Fig. 35.6 Blood circulation through the heart. Arrow heads indicate the course of circulation.

known as its SYSTOLE and DIASTOLE. The movements of the cardiac chambers are repeated in a cyclic manner during each heart beat. These events in each heart beat constitute a CARDIAC CYCLE. During the cardiac cycle, blood flows through the cardiac chambers in a specific manner and direction.

The phase during which both atria and ventricles are in diastole and are relaxed simultaneously, is called the JOINT DIASTOLE. During this phase, blood continues to flow into the atria through the great veins (superior and inferior venae cavae); blood also flows slowly from the atria to the respective ventricles through the open AV valves (Fig. 35.6). But no blood flows from the ventricles to the great arteries and the semilunar valves remain closed.

At the end of this phase, the next heart beat starts with the contraction of atria (ATRIAL SYSTOLE). As the atrium contracts, it forces most of its blood to the ventricle which is still in diastole (VENTRICULAR DIASTOLE). The atrium acts as a pump to collect and force the venous blood to the ventricle. During atrial systole, blood cannot pass back from the atria into the great veins, because the roots of the great veins are compressed by the atrial contraction to block their openings.

At the end of the atrial systole, the atrium relapses into diastole (ATRIAL DIASTOLE) and starts relaxing; during the atrial diastole venous blood again pass from the great veins to the atria to fill them up. Simultaneously with the onset of atrial diastole, the ventricles start contracting (VENTRICULAR SYSTOLE). The pressure rises immediately in the ventricle to exceed that in the atrium and the AV valves are shut sharply to prevent back-flow of blood from the ventricles to the atria. This sharp closure of the AV valves at the beginning of the ventricular systole produces a sound 'lubb' in the heart; this is the FIRST HEART SOUND heard during a heart beat by placing a stethoscope on the chest wall above the heart. Because the ventricular pressure still continues to be lower than the pressure in the great arteries and the semilunar valves consequently remain closed, the ventricles now contract as closed chambers. But as the ventricular systole progresses, the pressure in them increases rapidly and soon exceeds the pressure in the great arteries; semilunar valves now open and blood begins to be ejected into the great arteries. Still blood cannot flow from the ventricles to the atria because the AV valves continue to remain closed all

through the ventricular systole.

At the end of the ventricular systole, the ventricles go into diastole and start relaxing (VENTRICULAR DIASTOLE). As the atria are continuing their diastole, all the heart chambers are now in diastole; this is called the JOINT DIASTOLE. With the onset of ventricular diastole, the pressure falls in the ventricles below that in the great arteries. Immediately, the semilunar valves close sharply to prevent any back-flow of blood from the great arteries to the ventricles; the closure of the semilunar valves at the beginning of ventricular diastole produces a sound 'dup' in the heart—this is the SECOND HEART SOUND heard during a heart beat on placing a stethoscope on the chest wall. With the closure of the semilunar valves, the ventricles become closed chambers again, because the ventricular pressure is still higher than the atrial pressure and the AV valves consequently continue to remain closed. But as the ventricular diastole continues, ventricular pressure declines sharply and soon falls below the atrial

Inborn defects in the development of the heart or damaging effects of rheumatic fever frequently affects the cardiac valves. The affected valves may become leaky and fail to prevent back-flow of blood either from the ventricle to the atrium or from the aorta to the left ventricle. This may cause serious cardiac disorders. The defect is easily detected by changes in the nature of the heart sound (murmur) produced during the closure of the defective valves. These valves may be repaired or replaced surgically.

pressure. Then the AV valves open and blood starts flowing again from the relaxing atria to the relaxing ventricles. Towards the end of the joint diastole, the atria start their systole again to force the collected blood into respective ventricles. With the atrial systole, a new cardiac cycle starts.

### *Heart Rate and Pulse*

The human heart beats at the rate of about 70 per minute in the resting condition. Each time the heart beats, the ventricle pumps a volume of blood into the arteries already containing some blood. This causes a wave of distention to pass along the arteries immediately following the ventricular systole. This wave may be felt to flow along the arteries by placing a finger over an artery on the body surface. This wave of distention is called ARTERIAL PULSE and is normally felt by palpating radial artery near the wrist. As each heart beat sends one pulse along the arteries, normally the pulse rate per minute may be counted to know the heart rate.

The heart rate varies from species to species. Usually, the smaller the animal, the higher is its metabolic rate and consequently the greater is the need for the pumping action of the heart to supply nutrients and oxygen to the tissues. So, larger animals have lower heart rates than smaller ones. An elephant has a normal heart rate of about 25 per minute whereas mouse has a normal heart rate of several hundreds per minutes. The heart rate increases during exercise, fever, and emotions like anger and fear.

### *Automatic Rhythmicity of the Heart*

The automatic rhythmicity of the heart is its ability to contract spontaneously and at a regular rate. The heart beat results

from a wave of electrical potential, called the CARDIAC IMPULSE, spreading over the cardiac muscles of different heart chambers. Because the cardiac impulse originates in cardiac muscle fibres and is not brought to the heart by any nerve fibre, its origin is said to be MYOGENIC (myo = muscle, genic = originating from). Besides, the cardiac impulse is conducted along cardiac muscle fibres to reach the heart chambers. Although the cardiac impulse has a myogenic origin, the rate of its formation and conduction by cardiac muscle fibres may be changed by the actions of nerves. For example, the vagus reduces the rate of impulse formation from the SA node and its conduction along the conducting system of the heart; this slows the heart and may even stop it in diastole. The sympathetic nerve fibres increase the activity of the SA node to enhance the heart rate.

In mammals, the sinus venosus has completely merged with the wall of the right atrium and its last remnant is represented by a node of specialised cardiac muscle fibres on the right wall of the right atrium. This node is called SINOATRIAL NODE (SA node). Its muscle fibres possess the highest rhythmicity among all cardiac muscle fibres and can initiate excitatory waves at the highest rate. So, the cardiac impulse normally originates from the SA node. By determining the rate of discharge of the cardiac impulse, the SA node determines the rate of heart beat; so it is also called PACEMAKER of the heart. The cardiac impulse spreads directly from the SA node over the two atria to bring about their systole. It, however, cannot spread along the common cardiac muscle fibres from the atria to the ventricles, because in the mammalian heart, there is no continuity between the cardiac muscle fibres of

Sometimes, the SA node may become damaged or defective. It then fails to generate cardiac impulses at the normal rate. The heart beats become abnormally slow and irregular and ventricles fail to pump the required amount of blood. This can be remedied by the surgical grafting of an ARTIFICIAL PACE-MAKER instrument in the chest of the patient. The artificial pacemaker stimulates the heart electrically at regular intervals to maintain its beats. Thus, it replaces the SA node as the originator of the cardiac impulse.

As the cardiac impulse spreads over the cardiac chambers and causes their contractions, electrical changes sweep over the cardiac chambers in a specific sequence. These changes in the electrical potential over the heart can be recorded by fixing leads on the two arms, the left leg and the chest, and connecting them to an apparatus called (electrocardiograph). The record is called ELECTROCARDIOGRAM (ECG). Defects in cardiac functions or structures are reflected in changes in the pattern of electrical potentials recorded in the ECG. The ECG is, therefore, of immense diagnostic value in cardiac diseases.

the atria and those of the ventricles although the fibres of each individual chamber exist in a functional syncytium. However, a band of specialised cardiac muscle fibres exists on the interatrial septum called the ATRIOVENTRICULAR BUN-

DLE (AV bundle). It forms the only muscular continuity between atrial and ventricular muscles. The AV bundle descends from the AV node along the interatrial and the interventricular septa to enter the ventricles. Entering the ventricle, the AV bundle divides into RIGHT and LEFT BUNDLE BRANCHES; these descend along the two sides of the interventricular septum into the respective ventricles. From each bundle branch, specialised cardiac muscle fibers, called PURKINJE FIBRES, spread out and connect with common ventricular muscle fibres. The AV node, the AV bundle, the bundle branches and the Purkinje fibres constitute the conducting system of the heart. When the cardiac impulse spreads over the atria to reach the AV node, it runs along the AV node, the AV bundle, its branches and the Purkinje fibres to reach the ventricular muscle fibres. This causes the ventricles to contract. But because the impulse passes relatively slowly across the AV node, the atrial systole is over before the ventricles receive the impulse to start their systole. This is why the atrial systole normally precedes the ventricular systole.

Cardiac output is the volume of blood ejected by either ventricle into the arterial system. The cardiac output rises during exercise. In very severe exercise, it may rise to even 20 litres per minute, about four to fivefold the normal resting value of about 5 litres per minutes. The rise in the cardiac output helps the body in exercise by enhancing manifold the supply of nutrients and oxygen to the contracting muscles.

*Circulation*

The heart pumps blood into a closed circulatory system in vertebrates. The left ventricle ejects blood into the aorta, which gives off arteries to tissues and organs other than the lungs; blood is returned from these tissues and organs ultimately through two veins, superior and inferior vanae cavae to the right atrium. This is known as the SYSTEMIC CIRCULATION (Fig. 35.7). The right ven-

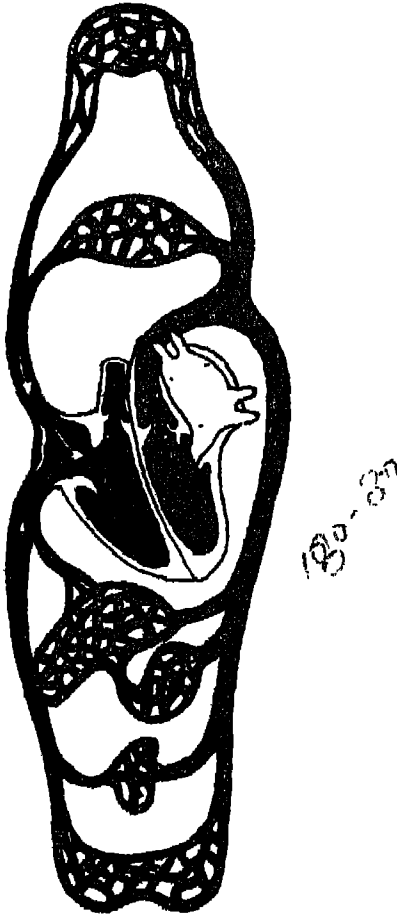


Fig. 35.7 Systemic circulation

tricle pumps blood into the pulmonary trunk which divides into pulmonary arteries going to the lungs; blood is returned to the left atrium from the lungs through the pulmonary veins. This is called the PULMONARY CIRCULATION (Fig. 35.8).

In some cases, a vein returning blood from a system of capillaries divides again into a second capillary system in the tissues before the blood can finally return to the heart. Such a vein is called a PORTAL VEIN together with the capillary system to which it supplies blood, a portal vein constitutes a PORTAL SYSTEM. For example, a hepatic portal vein returns blood from the intestine and breaks into a portal system of capillaries in the liver; this enables the liver cells to take up from the portal blood the nutrients brought by it from the small intestine. Similarly, venous blood is collected from near the hypothalamus of the brain by a hypophysial portal vein which forms a portal capillary system in the anterior part of pituitary gland; this portal system enables the hormones of hypothalamus to reach the anterior pituitary.

Arterial Blood Pressure: The pumping action of the heart maintains a pressure of blood in the arteries. This is called ARTERIAL BLOOD PRESSURE. It helps to propel blood at a high velocity along the arteries in the closed circulatory system. The blood pressure is far lower in the open circulatory system.

Blood Flow in Veins: Because the blood flows through narrow arterioles and capillaries to enter wider veins, the blood pressure is low in veins. At many places in the body, particularly in the inferior extremities, this blood pressure is not sufficient to drive the blood through the veins back to the heart. Veins have thinner walls than arteries and are more easily compressed. There are also many valves



Fig. 35.8 Pulmonary circulation

The arterial blood pressure is maintained by several factors. First is the pumping action of the heart. During each heart beat, the heart pumps a volume of blood into the arteries which already contain some volume of blood. The ejection of this additional volume of blood into the arterial system serves to raise the pressure of blood in the arteries during systole. This temporarily elevated pressure during the systole is called the SYSTOLIC PRESSURE and normally averages about 120 mm Hg. During diastole, the distended arteries recoil due to their elasticity and press on the blood contained in them. This serves to maintain the arterial blood pressure during diastole although no blood is being pumped into the arteries by the heart in diastole. The DIASTOLIC PRESSURE in a normal resting man averages about 80 mm Hg. So, during each heart beat, the arterial blood pressure rises to about 120 mm Hg in systole and falls again to about 80 mm Hg in diastole. The difference between the systolic pressure and the diastolic pressure is called the PULSE PRESSURE; it averages about 40 mm Hg in a normal person.

inside the veins. These valves permit the flow of blood in the veins towards the heart and prevent blood flow in the reverse direction. Contraction of muscles

compresses the veins to move the blood inside them. A change of body posture may also move the blood inside veins. In both cases, blood moves towards the heart



An abnormal rise in the arterial blood pressure is called **HYPERTENSION**. You may recall from the chapter 33 that a rise in blood cholesterol may lead to a deposition of cholesterol on the walls of blood vessels. This causes the arteries to lose their elasticity and get stiffened. This is called **ARTERIOSCLEROSIS** or hardening of arteries. The elasticity of the arterial wall moderates and reduces the rise in the arterial blood pressure. The stiffened arterial wall fails to exert this moderating effect on blood pressure. This results in hypertension in arteriosclerotic patients. A chronic vasoconstriction of arterioles may also cause hypertension, because the narrower the arterioles, the higher is the resistance against the blood flow in them and, consequently, the higher is the arterial blood pressure.

**HYPOTENSION** is an abnormally low arterial blood pressure. It may result from a chronic vasodilatation of arterioles, anaemia, blood loss due to bleedings, or a failure of the pumping action of the heart.

only, because the venous valves prevent the blood flow in the opposite direction. This is a major process for venous blood flow. If a person stands immobile for a long time, blood flow in the leg veins remain suspended. This may lead to an accumulation of fluid in his leg tissues and a consequent swelling of his feet. If he walks for some time, the swelling subsides as blood begins to circulate again in the veins.

### Lymph and Tissue Fluid

In the spaces between the cells of a tissue, there occurs a fluid called the **INTERSTITIAL FLUID** or tissue fluid. The exchanges of any solid, liquid and gas between blood and tissue cells always take place through this fluid. Under the pressure of blood in the capillaries some of the water and dissolved solutes are filtered out from blood plasma into tissue spaces to form the tissue fluid. The composition of this tissue fluid is very similar to that of plasma except that it has much less protein. This is because the capillary wall is impermeable to plasma proteins. Some of the tissue fluid enters tiny channels called **LYMPH**

**VESSELS** and the fluid collected in them is called **LYMPH**. These lymph vessels unite to form larger lymph vessels which ultimately drain into two large lymph vessels called thoracic duct and right lymphatic duct (Fig. 35.9). These open into the veins

Puffiness or oedema is caused by the increased capillary pressure, increased permeability of the capillary walls or decreased rate of return of lymph due to increased pressure in the veins. The permeability of the lymph capillaries is easily altered. For instance, in an infected wound, bacteria release chemicals which increase the permeability of the capillaries in that region, resulting in a local swelling. A swelling appears even in an uninfected injury because an injured tissue can somehow affect capillary permeability. The high permeability makes the lymph capillaries most likely route for the spread of microorganisms and cancer cells in the body.

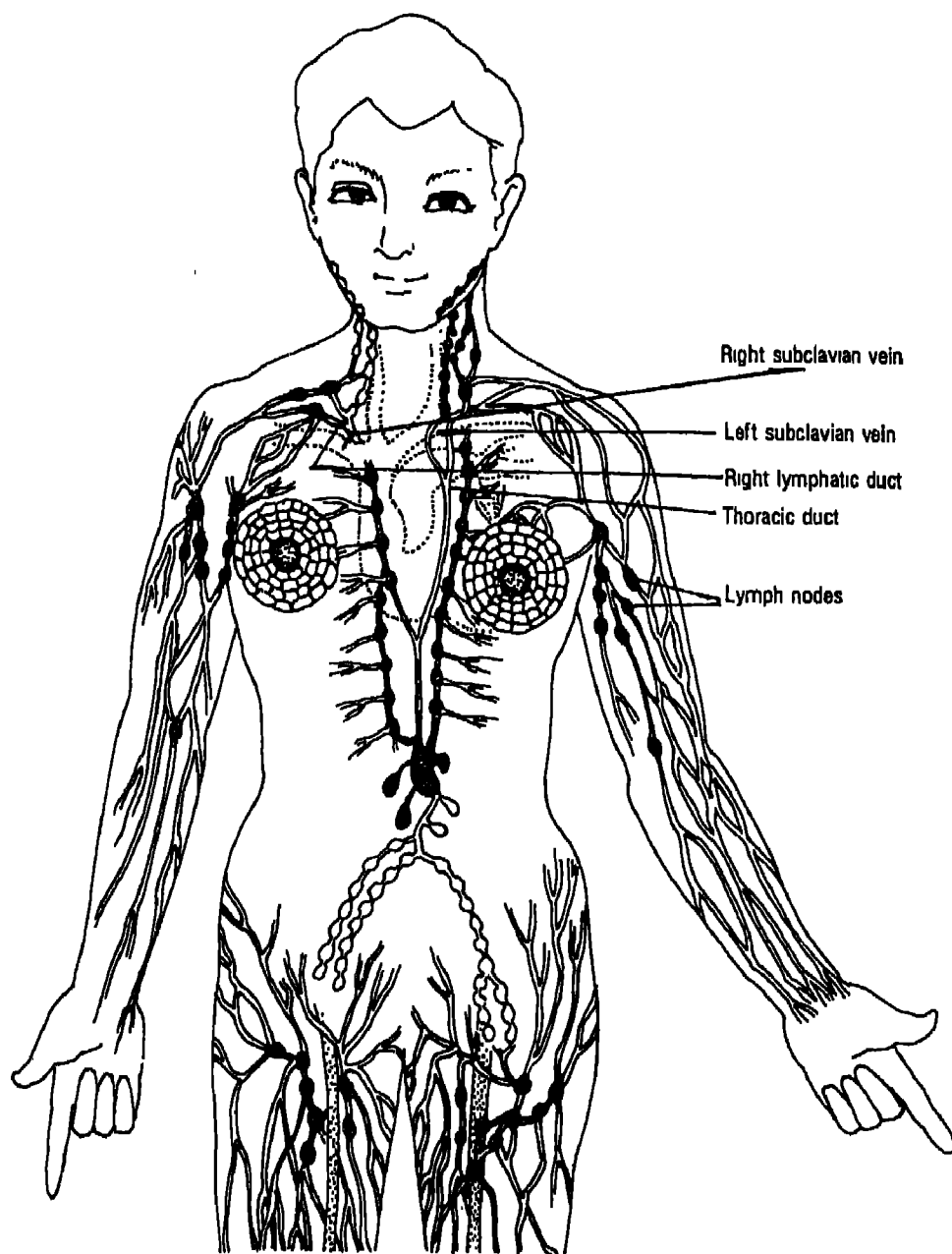


Fig. 35.9 The lymphatic system in a human body

The circulation of blood in the closed circulatory system was discovered and demonstrated for the first time by William Harvey (1578-1657), an eminent English physiologist. Harvey dissected a living snake to expose its heart. He then blocked the circulation in the inferior vena cava, by pressing that vein with forceps. The vein became empty of blood in the stretch between the forceps and the heart, the heart shrunk in volume and the heart beats slowed considerably. On releasing the forceps, the empty stretch of the vein was again filled with blood and the volume of the heart and the rate of heart beats increased. When the circulation was blocked in the aorta by compressing it with forceps, the stretch of aorta between the heart and the forceps became swollen with blood. On releasing the forceps, the engorgement of the aorta subsided. These findings showed that the great veins returned the blood to the heart while the aorta carried away the blood pumped by the heart.

Harvey obstructed the circulation in the arm veins of a man by fastening a tight bandage around his upper arm. This produced knots at the valves of the veins in the lower arm below the obstruction. He pressed the obstructed vein with a finger above one of the valves and ran the finger down the vein and away from the heart towards that valve. The swelling of the vein was found to increase at the valve, but not beyond it. When the obstructed vein was pressed below the valve with a finger and the finger was run upward towards the heart, the swelling at the valve subsided. These findings showed that the blood crosses the valves in veins always in a single direction so as to flow from the periphery to the heart, but cannot cross the venous valves in the opposite direction.

Harvey also showed that the heart contracts actively in the systole and ejects blood in jet into the arteries, the left ventricle pumping the blood into the aorta and the right one into the pulmonary trunk. He demonstrated that this ejection of blood into the arteries overfills them to make them swell and this swelling moves along the arteries in the form of a pulse. Thus, the arterial pulse coincides with the systole and not with the diastole.

Harvey delivered his first course of lectures on circulation at the Royal College of Physicians, London, in 1616. Finally, in 1628, he published his discovery of circulation in a treatise entitled "Exercitation anatomica de motu cordis et sanguinis in animalibus".

returning the lymph finally into venous blood and thus, to the general circulatory system. The movement of lymph is mainly due to the squeezing action of the surrounding muscles. As a result the lymphatic circulation is slow and uncertain. Exercise increases it. Normally, the rate of lymph formation is equal to the rate of its return to the blood stream. But some-

times, the formation rate of lymph exceeds the rate of its return to blood. The increased volume of fluid around the cells then creates a swelling, called dropsy or oedema.

#### *Functions of Lymph*

The lymph serves to return interstitial fluid into blood. Moreover, plasma pro-

tein macromolecules, synthesised by the liver cells, cannot pass into the blood vessels, but can diffuse into the lymph vessels through their wall. So, they come to the

blood through lymph. The lymph also carries absorbed fats and lipids from the small intestine to the blood in the form of chylomicron droplets.

## SUMMARY

The circulatory system circulates some extracellular fluid to different areas of the body. The circulating fluid transports nutrients, waste products, respiratory gases, metabolic intermediates and informational molecules between different tissues and organs. It also distributes water,  $H^+$ , chemicals and heat uniformly all over the body.

Sponges possess extensive canal systems in the body. Water from the surrounding medium circulates through the canals, carrying food and oxygen to the cells and taking away carbon dioxide and waste products from them. *Hydra* possesses a central water-filled body cavity or coelenteron, drawing water from the surrounding medium. Food, waste products and respiratory gases are exchanged between this water and the cells in the body wall.

More advanced animals carry blood as the circulating fluid and a circulatory system with the heart and blood vessels to conduct the blood. In many invertebrates such as prawns and insects, the blood pumped by the heart comes out from blood vessels and flows through open spaces and channels in the tissues before returning to the heart. This is called the open circulatory system. Vertebrates possess a closed circulatory system in which blood remains confined. Blood pumped by the heart passes through progressively smaller arteries to small arterioles and thence to capillaries; blood is returned from capillaries through venules and progressively larger veins to the heart. It never leaves the vessels normally. The valves located in the heart and blood vessels maintain the blood flow in a single direction in the circulatory system.

The heart is the pumping organ of the blood vascular system. The mammalian heart consists of two atria (auricles) and two ventricles. The sinus venosus has been totally fused with the right atrium which directly receives deoxygenated blood from most of the body through the great veins. The left atrium receives oxygenated blood from the lungs. The two atria are completely separated from each other by the interatrial septum and open into the respective ventricles through openings guarded by the AV valves. The two ventricles are also totally separated from each other by the interventricular septum and there is no mixing of deoxygenated and oxygenated blood in the heart. The left and right ventricles pump blood respectively into the aorta and the pulmonary artery, both openings being guarded by semilunar valves to prevent back-flow of blood from the arteries to the ventricles.

Cardiac cycle consists of events in the heart repeated cyclically during each heart beat. Contraction and relaxation of cardiac chambers (auricles or ventricles) are respectively called systole and diastole. When the atrium contracts, the ventricle is still in diastole and the blood collected in the atrium is pumped into the relaxing ventricle. Then the atrium starts relaxing and the ventricle starts its systole. The AV valve immediately closes producing the first heart sound, and prevents the back-flow

of blood from the contracting ventricle to the relaxing atrium. The rise of pressure in the contracting ventricle pushes the semilunar valves to open and blood is ejected from the ventricle to the great artery. Simultaneously, the atrium is in diastole and blood continues flowing into it from the great veins. When the ventricle ends its systole and starts relaxing, the semilunar valve closes sharply to prevent back-flow of blood from the great artery into the ventricle. This produces the second heart sound. With the ventricle in diastole, the AV valve opens again and blood again starts flowing from the atrium to the ventricle.

Heart beat results from a wave of electrical potential, called cardiac impulse, spreading over the cardiac chambers. The cardiac impulse is myogenic in origin; it originates from the cardiac muscle tissue itself, viz. from the sinoatrial node (SA node) in mammals. The impulse spreads from there over the atria causing their contraction. In the mammalian heart, the cardiac impulse first reaches the atrioventricular or AV node on the interatrial septum and then passes along the AV bundle and its branches to reach the Purkinje fibres in the ventricles. The Purkinje fibres conduct the impulse to the ventricular muscle fibres to cause their contraction. The nodes, the bundle, the bundle branches and the Purkinje fibres are made of specialised cardiac muscle fibres. The SA node is called the pacemaker of the heart because it originates the cardiac impulse and, consequently, determines the rate of heart beats.

Circulation of blood from the left ventricle to the tissues and back to the right atrium is called the systemic circulation; that from the right ventricle to the lungs and back to the left atrium is called the pulmonary circulation. Sometimes a vein, returning blood from capillaries, breaks again into a second set of capillaries in a tissue to form a portal system.

The pumping action of the heart maintains a pressure of blood in the arteries. This is called arterial blood pressure. It helps to propel blood at a high velocity along the arteries.

Blood flow is maintained in the veins largely by the compression of veins by contracting muscles, or by changes in posture. The valves located in veins allow blood to flow in a single direction to the heart and block any reverse flow.

The fluid in the spaces between tissue cells is called the interstitial fluid. It is formed by filtration of protein-free fluid from the blood. Exchanges of materials between blood and tissue cells involve the diffusion of these materials through the interstitial fluid. The interstitial fluid ultimately passes into lymph vessels to form a fluid called lymph. Lymph finally passes from the lymph vessels to the venous blood.

## QUESTIONS

1. Explain the following:

- Why does the atrial systole normally precede the ventricular systole?
- Why is the SA node called the pacemaker of the heart?
- Why does the ventricle relax as a closed chamber in the early phase of its diastole?

- (d) Why is there no mixing of deoxygenated and oxygenated blood in the human heart normally?
- (e) Why can you palpate the pulse on an artery in each heart beat?
- (f) Why does the lymph contain much less proteins than the plasma?
- (g) Why is the AV bundle essential for the conduction of cardiac impulse?
- (h) Why does the ventricle contract as a closed chamber in the early phase of its systole?
- (i) Why is the closed circulatory system more efficient than the open system?
- (j) Why does the left ventricle possess a thicker wall than the right ventricle?
2. Indicate whether following statements are true or false.
  - (a) Both the auricles of the amphibian heart open into the same ventricle.
  - (b) Prawn heart carries only oxygenated blood.
  - (c) Purkinje fibres are nerve fibres supplying the ventricular muscle.
  - (d) The first heart sound results from a closure of semilunar valves.
  - (e) The vagus nerve reduces the heart rate.
  - (f) The AV node normally initiates the cardiac impulse.
  - (g) Semilunar valves open during the ventricular diastole.
3. Contrast between the following:
  - (a) Open circulatory system and closed circulatory system.
  - (b) Pulmonary circulation and systemic circulation.
  - (c) Amphibian heart and mammalian heart.
  - (d) SA node and AV node.
  - (e) Atrial systole and ventricular systole.
  - (f) Mitral valve and semilunar valve.
  - (g) Effects of sympathetic nerves and vagus on the heart.
4. Fill in the blanks with appropriate words:
  - (a) The cardiac impulse originates from the \_\_\_\_\_ and is passed on to the AV bundle by \_\_\_\_\_.
  - (b) The \_\_\_\_\_ valves close shortly after the start of ventricular systole while the \_\_\_\_\_ valves close shortly after the diastole starts.
  - (c) Venae cavae drain the blood into the \_\_\_\_\_ atrium while pulmonary veins drain the blood into the \_\_\_\_\_ atrium.
  - (d) The mitral valve has \_\_\_\_\_ cusps while the aortic valve possesses \_\_\_\_\_ cusps.
  - (e) The human heart consists of \_\_\_\_\_ chambers while the fish heart has \_\_\_\_\_ chambers.
5. Describe the conducting system of the human heart.
6. How does blood flow through the heart during the different phases of the cardiac cycle?
7. Give the causes for the following:
  - (a) Heart sounds
  - (b) Non-mixing of deoxygenated and oxygenated blood in the mammalian heart.
8. Mark the odd one in each of the following series:
  - (a) Purkinje fibres; AV bundle; AV valve; SA node.
  - (b) Mitral valve; tricuspid valve; semilunar valve; venous valve.
  - (c) Thoracic duct; aorta; pulmonary vein; venae cavae.
  - (d) Human heart; fish heart; reptile heart; toad heart.

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## EXCRETION AND OSMOREGULATION

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*Lab 2: Excretion and Osmoregulation*

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EXCRETION is the elimination of waste products from the body. Metabolism of different chemical substances produces different waste products in the body. A large volume of carbon dioxide and water are produced by the metabolism of carbohydrates, fats and proteins. Carbon dioxide is easily eliminated as a gas by respiration. Some water is also vaporised from the lungs and eliminated in the expired air. Various non-volatile substances are either produced as a result of metabolism or taken in along with food. Being non-volatile, they have to be eliminated from the body in aqueous solutions or suspensions. Principal among them are NITROGENOUS SUBSTANCES such as AMMONIA, UREA and URIC ACID. These are produced as metabolic end-products of proteins. Proteins are major nitrogenous substances of food as well as body tissues. Hence, they form the main source of nitrogenous waste products. Metabolism of nucleic acids also produces small amounts of nitrogenous substances such as uric acid. The organism has also to

eliminate excess of vitamins, hormones and inorganic salts. Some water is eliminated for excreting all such non-volatile material. Moreover, the body is also required to excrete the water gained in excess of body requirements either from food and drinks or through the integument. This is necessary for preventing the dilution of body fluids with water.

The non-volatile solutes as well as water are mainly eliminated in the urine. The organs which form, store and void the urine constitute the urinary system.

### Nitrogen Excretion

The elimination of nitrogenous waste products is a major function of the excretory system. The principal nitrogenous waste product varies from species to species—proteins are catabolised most commonly into ammonia, urea or uric acid according to the species.

### Ammonotelism

Ammonotelism is the urinary elimination of nitrogen mainly in the form of ammo-

nia. Ammonia is the basic nitrogenous catabolite of proteins. Ammonia is highly soluble in water and highly toxic to the animal. So, its concentration must be kept very low in the blood. For this, ammonia should be eliminated as rapidly from the body as it is formed. A large volume of water is needed by the animal to dissolve ammonia and eliminate it from the body. So, its elimination in urine involves considerable loss of water from the body. But this poses no problem for animals living in aqueous habitat. Many aquatic invertebrates, bony fishes and aquatic amphibians such as salamanders excrete ammonia as the main nitrogenous waste product in the urine. They are called **AMMONOTELIC ANIMALS**.

#### *Ureotelism*

Ureotelism is the urinary elimination of nitrogen mainly as urea. Many animals cannot readily get as much water as is required for the speedy elimination of ammonia. In the liver of such animals, ammonia is immediately combined with carbon dioxide to form urea. The synthesis of urea from ammonia requires energy. Still it is very helpful to the animal because urea is far less toxic than ammonia and the animal can afford to excrete it at a slower rate than ammonia itself. Urea is very soluble in water and needs a considerable volume of water for its elimination. So, it can serve as the principal nitrogenous waste product only when the animal can afford either to excrete sufficient volumes of water, or to concentrate urea considerably in the urine, or to retain considerable amounts of urea in the blood and body fluids. **UREOTELIC ANIMALS** include man and all other mammals, even aquatic mammals like whales and seals, and desert mammals such as camels and

kangaroo rats, terrestrial and semi-aquatic amphibians like toads and frogs, cartilaginous fishes (elasmobranchs) such as sharks and sting rays and aquatic or semi-aquatic reptiles like alligators, terrapins and turtles are also ureotelic. Man can concentrate urea in the urine more than hundred times its concentration in blood.

Earthworms excrete ammonia when sufficient water is available, but eliminate urea instead of ammonia in drier environments. *Xenopus* toad, and lung fishes are normally ammonotelic when living in water; but they turn ureotelic and retain urea in their blood when lying immobile and dormant in moist air or mud during summer months. Amphibian larvae, the tadpoles, are aquatic and ammonotelic; but they switch over to ureotelism and start forming urea during their metamorphosis into adult terrestrial forms. Sharks retain so much urea in their blood that their blood osmotic pressure approaches that of sea-water; this minimises water loss from their body to the concentrated saline water of the sea.

#### *Uricotelism*

Uricotelism is the elimination of nitrogen mainly as uric acid. Ammonia produced by protein catabolism is converted to uric acid in the liver of **URICOTELIC ANIMALS**. Synthesis of uric acid involves far higher expenditure of energy than the synthesis of urea. But excretion of uric acid instead of urea is of greater advantage to land animals and birds with very limited access to



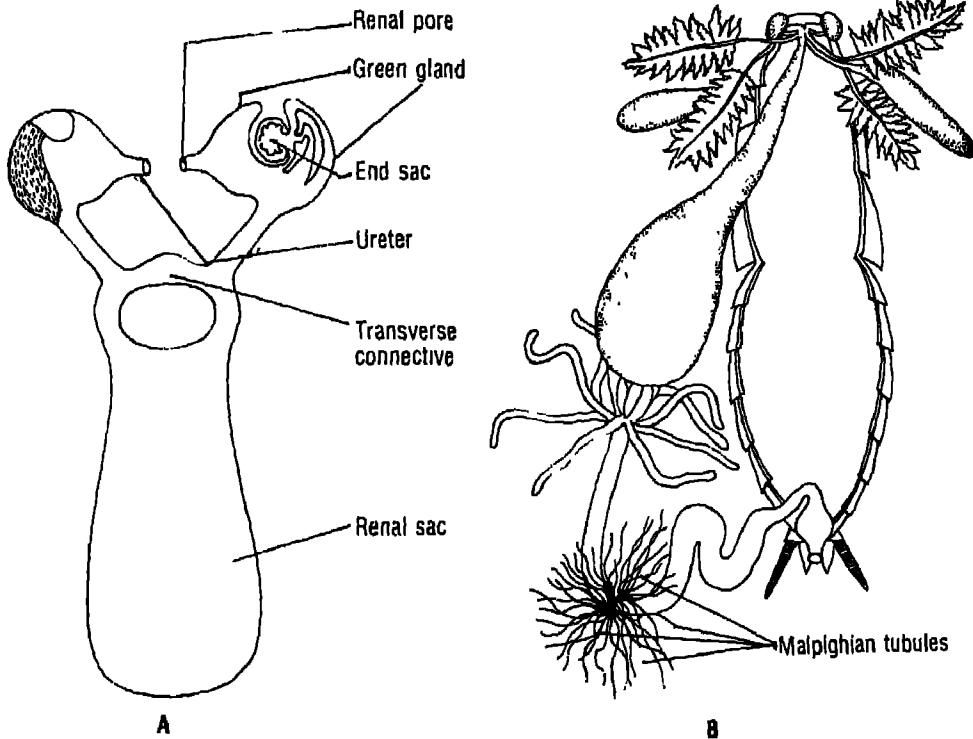


Fig.36.1 A. Excretory organs in prawn; B. Malpighian tubules of cockroach (insect) attached with the alimentary canal

water because it is far less toxic and being insoluble in water, does not require much water for its elimination. Birds, land reptiles, insects, land snails and some land crustaceans are uricotelic. You must have noticed that the droppings of birds and lizards consist of insoluble white and brownish black material suspended in a little aqueous fluid. The white material consists of insoluble crystals of uric acid and urates; suspended in a small volume of water, it forms the urine. The greyish or brownish black material is the faeces. So high is the concentration of uric acid in

bird-droppings that uric acid has been commercially extracted from bird-droppings (guano) collected particularly from uninhabited marine or littoral islands.

### Excretory System

The excretory system consists of organs and tissues participating in the removal of waste products. Some of these excretory organs constitute the urinary system which forms and eliminates urine and helps mainly in the excretion of nitrogenous waste-products, water and some

Though ureotelic, man excretes a small amount of uric acid in his urine. It is formed from nucleic acid and is too little in amount as compared to the total urinary nitrogen. In some patients, either the formation of uric acid is abnormally enhanced by metabolic defects or its urinary elimination becomes defective. This raises the concentration of uric acid in their body fluids. Being almost insoluble, uric acid is deposited in soft tissues including joints, cartilages and kidneys. Such patients consequently develop gout and kidney failure.

mineral salts. Besides the urinary system, there are some accessory excretory organs and tissues such as the skin, lungs and liver. The mode of excretion varies in different kinds of animals.

#### *Excretory Organs of Invertebrates*

In sponges, waste products are drained out through their water canal system; in *Hydra*, cells release waste products into the coelenteron from which it goes out through the hypostomal opening. FLAME CELLS perform excretory function in the body of tape worms. Annelids have coiled tubules forming the excretory organs called NEPHRIDIA. Prawns have GREEN GLANDS and insects possess MALPIGHIAN TUBULES as organs of excretion (Fig 36.1).

#### EXCRETORY VESSELS AND FLAME CELLS

Tapeworm, liver fluke and *Planaria* possess long interconnected excretory vessels which open to the outside through pores in the body-wall. Fine capillary vessels, connected to the excretory vessels, terminate in flame cells (Fig. 36.2). The flame cell is a large cell at the tip of a capillary vessel. Its cytoplasm is hollowed out by the blind end of the capillary; so, the cell surrounds a large central cavity continuing into the capillary vessel. Many cilia project from the cell surface into the central cavity. Soluble waste products diffuse from neighbouring cells into the flame cell. The latter excretes an aqueous solution of waste products as the urine into the central cavity bounded by its cytoplasm. Ciliary movements of the flame cell propel the urine from the central cavity to the capillary vessel. The name 'flame cell' comes from the flickering appearance of moving cilia under the microscope. The urine in the capillary vessel moves through progressively bigger vessels by ciliary movements on their walls and finally flows to the exterior through the pores in the body wall.

#### NEPHRIDIA

Earthworm, leech and other annelids possess an excretory system consisting of many long or short, coiled or otherwise modified tubules called NEPHRIDIA (Fig 36.3). They occur in pairs in many body segments. Each typical nephridium starts from a round ciliated funnel called NEPHROSTOME which opens into the body cavity (coelom); the lumen of the tubule communicates with the body cavity through

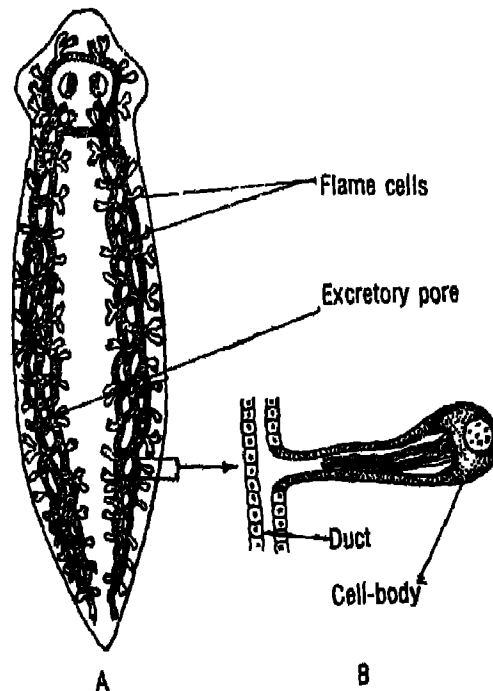


Fig.36.2 A. Excretory system in *Planaria*  
B. Enlarged view of a flame cell

the nephrostome. The nephridial tubule passes in a zig-zag course through the body, it is invested by blood capillaries and possesses ciliated cells lining its lumen. A typical nephridium finally opens outside the body through a small circular opening or NEPHRIDIOPORE in the body wall. But some nephridia open into collecting ducts draining into the alimentary canal. The nitrogenous waste formed in nephridia is propelled by ciliary movements and ultimately flows either to the exterior or into the alimentary canal.

#### GREEN GLANDS

The principal excretory organs of prawns are paired GREEN GLANDS. They are located within the second antennae which are the second pair of appendages attached to the anterior part of the body. Each green gland consists of an END SAC, a LABYRINTH and a BLADDER (Fig 36.1). The end sac is a small bean shaped structure carrying blood lacunae in its wall. Urine is first formed in the lumen of the end sac from the blood in the lacunae. Urine flows from the end sac to the thin, branched and tortuous tubules of the labyrinth. Urine flows from the labyrinth to a large sac-like bladder, which stores it temporarily. A duct called the ureter leads from the bladder to the base of the antenna where it opens to the exterior. Urine is voided from the bladder through the ureter. The end sac and the labyrinth seem to eliminate ammonia and uric acid respectively in the urine. The bladder opens also by a duct into a large thin-walled RENAL SAC.

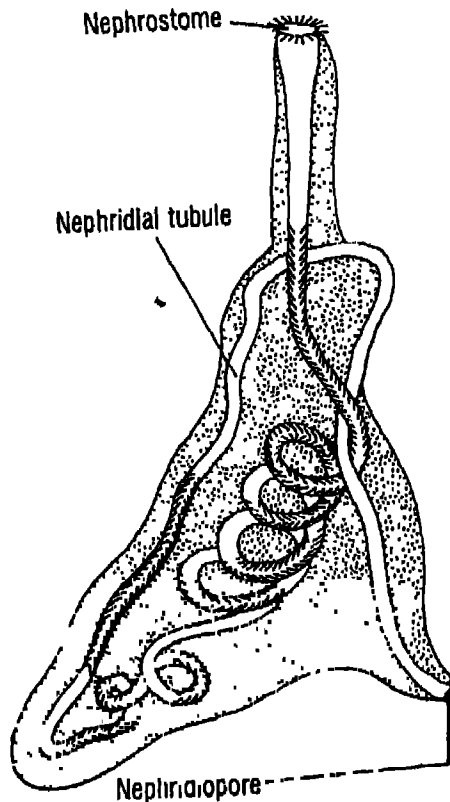


Fig.36.3 Nephridium of *Nereis*

#### MALPIGHIAN TUBULES

The principal excretory organs of most insects, millipeds, spiders and scorpions consist of fine, spiral or convoluted, thread-like tubules called MALPIGHIAN TUBULES (Fig 36.1). They lie in the body fluid called hemolymph, run beside the alimentary canal and open into the latter. The other end of each tubule is blind and remains immersed in the hemolymph. Water and nitrogenous waste products such as uric acid and guanine enter the tubular lumen from the hemolymph to form the urine. Movements of the tubular wall conduct the urine finally to the alimentary canal.

#### Vertebrate Urinary System

Kidneys are the urine-forming organs of vertebrates including mammals. The urinary system of mammals consists of two kidneys, two ureters, a urinary bladder

and a urethra (Fig 36.4). The two flattened bean-shaped kidneys are located inside the abdomen on two sides of lumbar vertebrae and against the posterior abdominal wall. Each kidney is covered

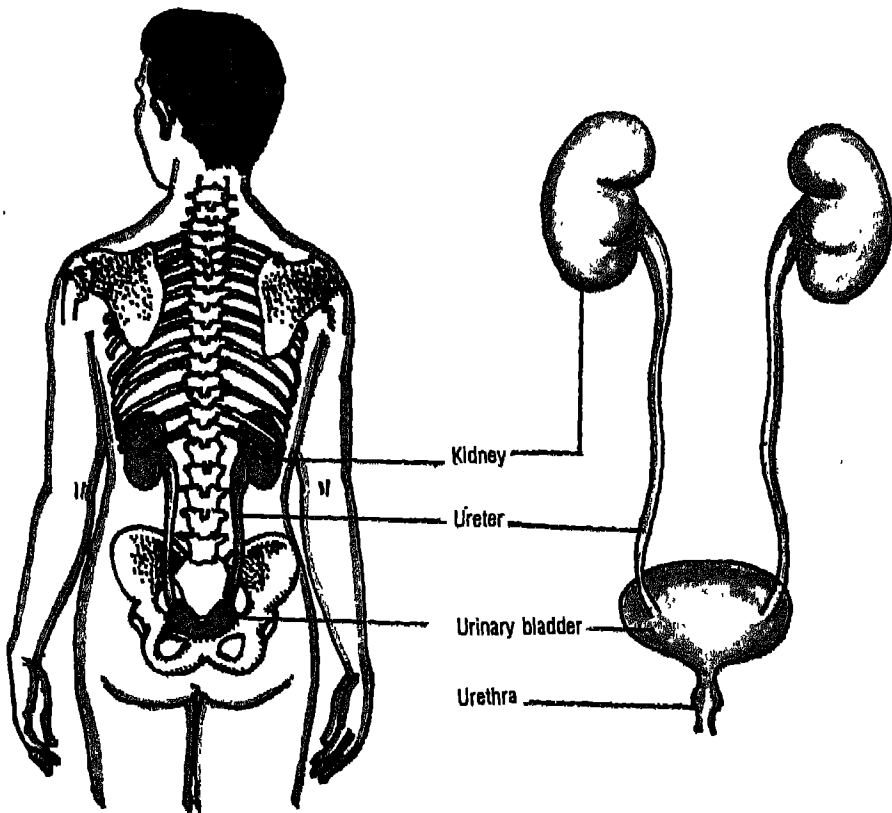
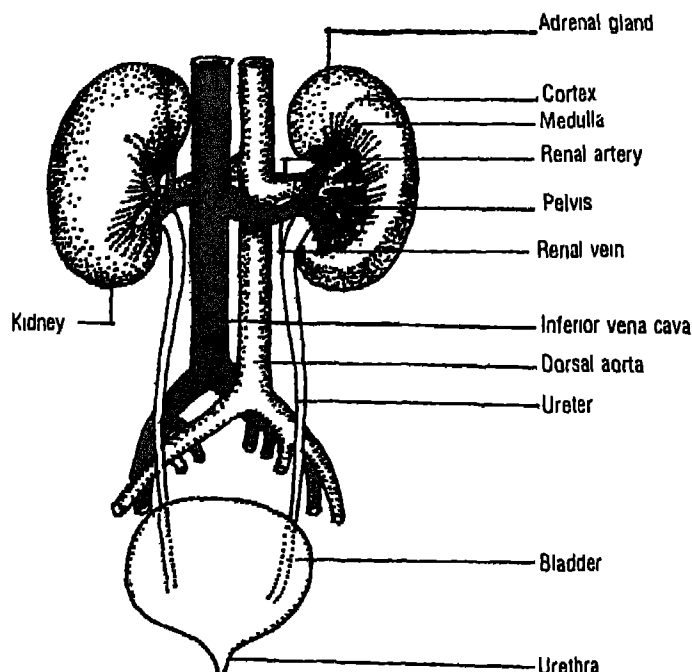


Fig.36.4 Urinary system of a mammal (human)

by a tough capsule. The human kidney measures about 10 cm in length, about 5 cm in breadth and about 9 cm in thickness. On the concave side of the kidney, there is a longitudinal opening, called the **HILUM**. The hilum leads to an extensive, flat, funnel shaped space called the **RENAL PELVIS** (Fig 36.5). The pelvis is almost completely surrounded by the kidney tissue. The kidney consists of an outer layer of tissue called the **RENAL CORTEX** and an inner tissue called the **RENAL MEDULLA**. Conical pyramid-shaped masses of the renal medulla project into the renal pelvis

and are called **MEDULLARY PYRAMIDS**. Urine is formed by a vast number of minute tubular structures called **NEPHRONS** which form the structural and functional units of the kidney (Fig. 36.6). Nephrons and collecting tubules can be seen in a section through the kidney. Nephrons lie partly in the renal cortex and partly in the renal medulla. Collecting ducts collect the urine from nephrons and conduct it into bigger ducts. These drain the urine into the renal pelvis through minute openings at the apices or PAPILLAE of the pyramids. The renal artery and the renal vein respec-



**Fig.36.5** The kidneys and the associated structures in man. The left kidney is partially dissected to show the internal structure.

tively enters and leaves the kidney through its hilum.

A thin muscular tube called the **URETER** emerges from the hilum of each kidney. Urine enters the ureter from the renal pelvis and is conducted along the ureter by peristaltic waves on its wall. Ureters from both the kidneys finally open into a hollow muscular sac called the **URINARY BLADDER**. Thus, the urine from both kidneys is drained into the bladder which stores it temporarily. Bladder and ureters are lined by transitional epithelium which

In birds and reptiles, ureters and the rectum open into a sac called the **CLOACA** which stores both urine and faeces, and reabsorbs water from them. The cloaca opens to the outside through a cloaca aperture. In reptiles, the urinary bladder is a sac attached to the wall of cloaca.

may be considerably stretched without getting torn when the bladder and ureters

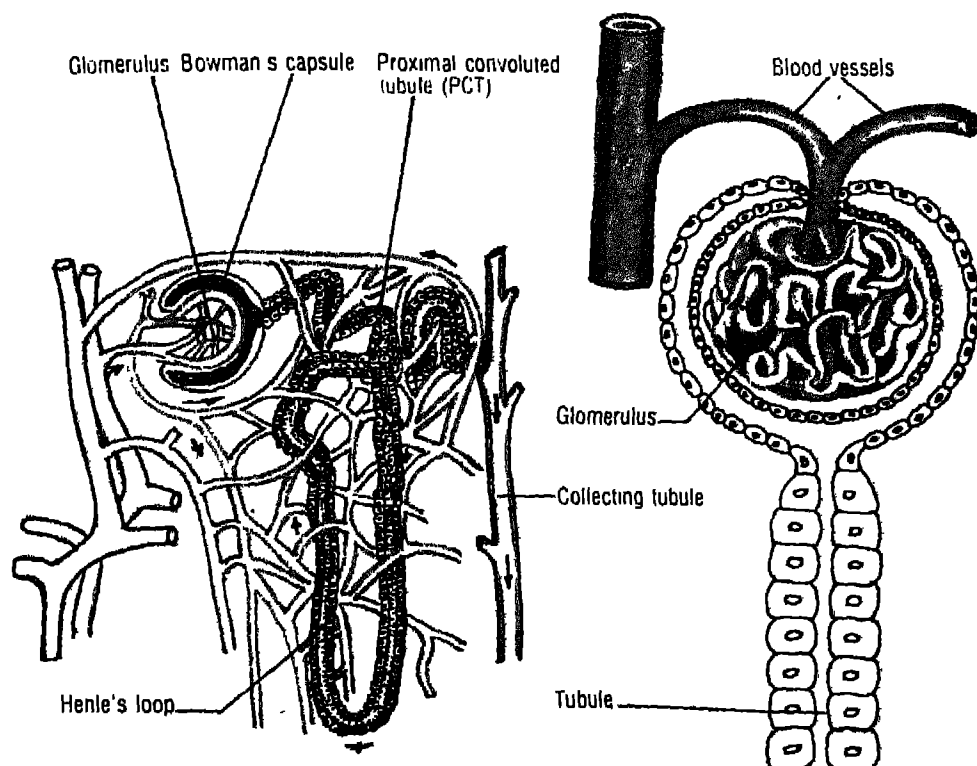


Fig. 36.6 A. Nephron—the unit which builds up a kidney; B. Bowman's capsule

are filled with urine.

A membranous tube called URETHRA arises from the neck of the bladder and conducts urine to the exterior. The muscular urethral sphincters keep the urethra closed except during the voiding of urine.

MICTURITION is the act of voiding the urine. Besides functioning as a temporary reservoir of urine, the bladder also evacuates the urine by the process of micturition at suitable intervals. When enough

urine has accumulated in the bladder to distend the bladder and raise its pressure sufficiently, a spontaneous nervous activity (reflex) is initiated; this causes the smooth muscles on the bladder wall to contract and the urethral sphincters to relax. Urine consequently flows from the bladder through the urethra to the exterior. But it is prevented from flowing back into the ureters, because the terminal part of each ureter passes obliquely through

the bladder wall and is consequently closed due to compression by the contracting bladder muscles. Micturition may be voluntarily inhibited for a prolonged interval until the bladder pressure rises too high. On the contrary, micturition may also be voluntarily initiated even before sufficient urine has collected in the bladder.

### Accessory Excretory Organs

Besides the urinary system, some other organs and tissues function as accessory excretory organs. The skin, lungs and liver in vertebrates are accessory excretory organs.

#### *Excretory Role of Skin*

In many aquatic animals, ammonia may be excreted into the surrounding aqueous medium by diffusion through the integument. But the integument is far less permeable in land animals; this has evolved for preventing the loss of water through the integument. But the skin still retains some minor excretory role in many land animals. Human skin possesses glands for secreting two fluids on its surface, viz. sweat from sweat glands and sebum from sebaceous glands.

Sweat is an aqueous fluid containing in solution mainly sodium chloride, lactic acid, urea, amino-acids and glucose. It serves in excreting mainly water and sodium chloride, and small amounts of urea and lactic acid.

Sebum is a wax-like secretion which eliminates some lipids such as waxes, sterols, other hydrocarbons and fatty acids on the skin.

#### *Excretory Role of Lungs*

Lungs regularly participate in the excretion of some volatile materials by respira-

Large amounts of sodium chloride are excreted in sweat during profuse sweating. So, muscle cramps may occur due to salt deficiency if only water is drunk instead of a dilute salt solution to quench the thirst during heavy sweating. Lactic acid concentration in sweat may significantly exceed that in the blood and urine during and after heavy work which produces much lactic acid by glycolysis. However, the volume of sweat varies from negligible to 14 litres a day, rising with activity and temperature, because sweat is principally meant for heat loss by its evaporation from the skin surface. So, the amount of water, sodium chloride, urea or lactic acid excreted in sweat varies not with the need of the body to excrete them, but with the need to cool the body by secreting sweat.

tion. The entire volume of carbon dioxide, produced in the body, and some moisture are regularly excreted in the expired air.

#### *Excretory Role of Liver*

The liver is the principal organ for the excretion of cholesterol, bile pigments (bilirubin and biliverdin), and inactivated

In infective hepatitis or liver damage due to chloroform poisoning, the liver fails to eliminate bile pigments in the bile. This produces jaundice with yellowish hue of the skin and mucosa due to high blood levels of bile pigments.



products of steroid hormones, some vitamins and many drugs. It secretes these substances in the bile. They are carried by the bile to the intestine and are ultimately eliminated with the faeces.

### Urinary Elimination of Waste Products in Man

Kidneys excrete in the urine nitrogenous waste products such as urea, uric acid and ammonia, water, inorganic salts such as sodium chloride, and various other substances. For this, kidneys secrete urine continuously in their nephrons.

### Nephrons

Nephrons are the functional units of kidneys (Fig 36.6). Each kidney possesses about 1.2 million nephrons in man. The nephron is a thin, long, twisted tubular structure, originating in the renal cortex and coursing partly through the cortex and partly through the renal medulla. Nephrons present a vast total surface area for exchange of materials between the urine in their lumen and the cells on their wall.

The tubule of each nephron begins as a cup-shaped capsule made of two membranes. It is called BOWMAN'S CAPSULE and encloses in the hollow of the cup a globular tuft of capillaries called the GLOMERULUS (Fig 36.6). The inner membrane of the Bowman's capsule is applied closely on the walls of glomerular capillaries; its outer membrane continues into the wall of the next segment of the tubule. The space or lumen between the membranes of the Bowman's capsule is continuous with the lumen of subsequent portions of the tubule. The Bowman's capsule and the glomerulus together form a globular body called the RENAL CORPUSCLE. Blood enters the glomerular capillaries through

an AFFERENT ARTERIOLE and leaves the glomerulus through an EFFERENT ARTERIOLE. Urine is primarily formed by the filtration of a protein-free fluid (GLOMERULAR FILTRATE) from the glomerular capillary blood into the lumen of the Bowman's capsule; the force for this filtration is mainly provided by the blood pressure.

The neck of the Bowman's capsule continues into a long, highly coiled and twisted tubule called the PROXIMAL CONVOLUTED TUBULE (PCT). It is also located in the renal cortex. The PCT continues into a thin-walled straight tubule which descends from the cortex to the renal medulla, then loops back and returns to the cortex as a straight thick-walled tubule parallel to the thin limb. This U-shaped loop-like segment of the tubule is called the HENLE'S LOOP (Fig 36.6); it consists of the thin DESCENDING LIMB and the thick ASCENDING LIMB. Henle's loops are long in mammals and birds which secrete hyperosmotic urine, but are short or absent in other vertebrates like reptiles which cannot secrete hyperosmotic urine. The Henle's loop continues into another segment of coiled and twisted tubule called the DISTAL CONVOLUTED TUBULE (DCT). The terminal portion of the DCT is a relatively straight short tubule called the COLLECTING TUBULE. It is also located in the renal cortex. Collecting tubules of a number of nephrons open into a bigger duct called the COLLECTING DUCT (Fig 36.6). The glomerular filtrate flows from the Bowman's capsule through the PCT, Henle's loop, DCT, collecting tubule and collecting duct. These tubules reabsorb considerable amounts of water and different solutes from the filtrate, changing it to the urine. The collecting duct runs down to the medulla again, conducting the col-

lected urine towards the medulla. Collecting ducts unite with each other in the medulla to form still larger DUCTS OF BEL-LINI. These run through the renal pyramids and open into the renal pelvis. Thus, the urine is finally drained into the pelvis. The efferent arteriole emerging from a glomerulus gives a capillary network around the tubules in the cortex. It also gives rise to some parallel, wide, thin-walled, straight capillaries, called VASA RECTAE. Each vasa recta first descends into the medulla, then loops back to the cortex and finally drains into a venule. The loops of vasa rectae lie close to the Henle's loops of nephrons. They help to retain reabsorbed ions and urea in the medullary interstitial fluid, thus maintaining its high osmotic pressure.

### *Composition of Urine*

Normally an adult man secretes about 1-1.8 litres of urine in 24 hours. The volume of urine depends upon the fluid intake, the level of physical activity and the temperature. Excessive intake of fluids increases the urine volume; restricted water intake, profuse sweating and heavy work reduces the urine volume. Urine is a transparent, yellowish, aqueous fluid. It is usually acidic in reaction and hypertonic, i.e. it has a higher osmotic pressure than the blood plasma. Its specific gravity, normally ranges between 1.003 and 1.040. It has a characteristic odour. When allowed to stand, it smells strongly of ammonia due to bacterial degradation of urea to ammonia.

Urea is the chief nitrogenous constituent of human urine. Other nitrogenous constituents of normal urine include ammonia, uric acid, creatinine and hippuric acid. About one-fourth of the solids is accounted for by sodium chloride; it is the

principal mineral salt in urine. Small quantities of other inorganic salts such as chlorides, sulphates and phosphates of potassium, calcium and magnesium are also present. Non-nitrogenous organic constituents include small amounts of vitamin C, oxalic acid and phenolic substances. Glucose is normally negligible in amount. Proteins (albumin), bile salts, bile pigments, glucose and ketone bodies occur in urine in various pathological conditions only.

### *Formation of Urine*

Nephrons form urine by a combination of three processes: (i) FILTRATION of a protein-free filtrate from the plasma into the Bowman's capsule, (ii) REABSORPTION of some of the filtered materials in the renal tubules, and (iii) SECRETION of some other material by the tubules into the filtrate.

A protein-free fluid (GLOMERULAR FILTRATE) is filtered from the blood of glomerular capillaries to the lumen of the Bowman's capsule. This process is called GLOMERULAR FILTRATION. The driving force for this filtration is provided by the difference between the glomerular blood pressure and the sum of the osmotic pressure of plasma proteins and the pressure of the filtrate already present in the Bowman's capsule. This filtering force normally averages about 10 mm Hg in man. It normally filters about 125 ml of the filtrate in the two kidneys every minute. About one-fifth of the total volume of plasma flowing through the kidneys is thus filtered out as the glomerular filtrate. The filtration occurs across the membrane made of the glomerular capillary wall and the inner membrane of the Bowman's capsule. The pores of this filtering membrane are impermeable to large molecules or

particles. Large particles like blood cells and protein macromolecules do not normally enter into the glomerular filtrate. But smaller molecules like glucose, urea, creatinine, amino-acids and mineral salts are filtered into the Bowman's capsule in concentrations more or less similar to their respective concentrations in the plasma. The filtrate, therefore, almost resembles the protein-free plasma in composition and osmotic pressure.

As the glomerular filtrate courses through the tubules, its composition, osmotic pressure and pH change progressively, this is largely due to reabsorption of water and many solutes from it in the tubules. This process is called TUBULAR REABSORPTION. There are two mechanisms for tubular reabsorption—active and passive. Substances which are of considerable importance to the body such as glucose and amino-acids are reabsorbed actively. Such ACTIVE REABSORPTION is very rapid and continues even when the concentration of the substance is far lower in the glomerular filtrate than in the blood.

Some other substances are re-absorbed

from the tubules slowly by the physical process of diffusion, only so long as their concentrations in the glomerular filtrate exceed their respective concentrations in the blood. So, these substances can never be totally re-absorbed from the urine, e.g. urea, ammonia, creatinine and ketone bodies. Water is also reabsorbed by the passive physical process of osmosis.

THE PROXIMAL CONVOLUTED TUBULE (PCT) actively reabsorbs almost the total amount of glucose, most of the amino-acids and vitamin C, about 70 per cent  $\text{Na}^+$ , nearly 75 per cent of  $\text{K}^+$ , and a large amount of  $\text{Ca}^{2+}$  from the glomerular filtrate.  $\text{Cl}^-$  is reabsorbed by diffusion from the PCT. 75 per cent of the water of the filtrate is also reabsorbed here by osmosis during the reabsorption of solutes.

About 5 per cent of the water in the filtrate is reabsorbed by osmosis from the DESCENDING LIMB of Henle's loop due to the higher osmotic pressure of the medullary extracellular fluid maintained by vasa rectae.

The ASCENDING LIMB of Henle's loop actively reabsorbs the remaining 25 per cent of the filtered  $\text{K}^+$  and some amounts of

Either the total amount or most of the substance may be reabsorbed actively. Such substances are called HIGH THRESHOLD SUBSTANCES and are excreted in the urine only when their blood concentration is considerably high, e.g. glucose and amino-acids. RENAL THRESHOLD of a substance is its highest concentration in the blood, up to which it is totally reabsorbed from the glomerular filtrate. If its blood concentration exceeds the renal threshold, so much of it is filtered in the glomerular filtrate that it can no longer be totally reabsorbed; consequently, it appears in the urine. For example, glucose is a high threshold substance — its renal threshold is as high as about 180 mg per 100 ml; it is totally reabsorbed and does not appear in the urine so long as its blood level does not exceed 180 mg. But when its blood level exceeds 180 mg, some of the filtered glucose is left unabsorbed in the tubules and consequently appears in the urine.

The blood urea level rises abnormally (uremia) in patients suffering from renal failures. In uremia patients, an artificial kidney is used for removing accumulated waste products like urea from the blood by a process called HEMODIALYSIS. Blood is taken out from an artery of the patient, cooled to  $0^{\circ}\text{C}$ , mixed with an anticoagulant (heparin) and then pumped into the apparatus called the artificial kidney. In this apparatus, blood flows through channels or tubes bounded by cellophane membrane. The membrane is impermeable to macromolecules such as plasma proteins, but permeable to small solutes such as urea, uric acid, creatinine and mineral ions. The membrane separates the blood flowing inside the channels or tubes from a dialysing fluid flowing outside the membrane. The dialysing fluid contains some small solutes and mineral ions, but does not contain waste products such as urea, uric acid and creatinine. So, these waste products diffuse from the blood to the dialysing fluid across the cellophane membrane. Thus, the blood is cleared of considerable amounts of urea, uric acid, creatinine and other waste products, but does not lose the plasma proteins because the cellophane membrane is impermeable to them. Such a process of separating small solutes from macromolecular colloids with the help of a membrane is called dialysis. The blood coming out from the apparatus is warmed to body temperature, mixed with an anti-heparin to restore its normal coagulability, and returned to a vein of the patient. Hemodialysis saves and prolongs the life of many uremic patients.

$\text{Cl}^-$ . Some  $\text{Na}^+$  is also reabsorbed by diffusion due to the electrostatic attraction of the reabsorbed  $\text{Cl}^-$ . But no water is reabsorbed with the solutes, because the ascending limb is impermeable to water. So, the filtrate becomes diluter (hypotonic) than the plasma as it flows through this limb.

The DISTAL CONVOLUTED TUBULES (DCT), COLLECTING TUBULE and COLLECTING DUCT actively reabsorb some  $\text{Na}^+$  from the filtrate and in exchange, excrete some  $\text{K}^+$  in the urine. Some  $\text{Cl}^-$  is reabsorbed by diffusion from the DCT.

The third process in urine formation consists of TUBULAR SECRETION. This is of considerable importance in marine fishes and desert amphibians. These animals possess no glomerulus in their nephrons; they form urine by secreting solutes such

as urea, creatinine and mineral ions into their tubules. Tubular secretion is of far less importance in mammals. But most of the  $\text{K}^+$  eliminated in the mammalian urine is secreted by the distal convoluted tubule and collecting ducts in exchange of the reabsorbed  $\text{Na}^+$ . The distal convoluted tubule and collecting tubule also secrete uric acid and ammonia in the urine.

Thus, urine is formed in the nephron by a combination of glomerular filtration, tubular reabsorption and tubular secretion.

#### *Osmoregulation by Kidney*

Kidneys play an essential role in maintaining the concentration and osmotic pressure (osmoconcentration) of blood. When water intake of an animal is very

high, the urine excreted has to be **HYPO-TONIC** in order to remove the excess of water. Contrarily, when there is a threat of excessive water loss from the body, the urine needs to be hypertonic to reduce the loss of water with urine. In this way, the osmotic concentration of the blood is maintained. Almost all vertebrates including mammals can produce hypotonic urine, diluter and lower in osmotic pressure than their blood. Many fresh-water vertebrates like fishes secrete very dilute urine. For this, an isotonic fluid having the same osmoconcentration as the blood, is first filtered into the Bowman's capsule from the blood; some solutes are then reabsorbed from the filtrate in the tubules. This leaves the urine diluter than the blood. Hypotonic urine, therefore, serves to eliminate excess water from the body so as to raise the osmoconcentration of the blood to normal.

The land and marine animals may lose excessive amounts of water from their body; this poses the threat of a rise in osmoconcentration of their blood. Mammals and birds can excrete hypertonic urine which is more concentrated than their blood. For this, an isotonic glomerular filtrate is first filtered into their Bowman's capsule; tubules then reabsorb from this filtrate a large volume of water, not accompanied by the reabsorption of proportionate amounts of solutes. This leaves the urine more concentrated than the blood. This is very effective in reducing the urinary loss of water.

The vertebrate kidney is extremely flexible in operation. Depending on the availability of water and salts it excretes large quantities of dilute urine when water is abundant and small amounts of concentrated urine when water needs to be conserved. The fluid volume and osmolarity

at the kidney gets regulated largely by the movement of  $\text{Na}^+$ ,  $\text{Cl}^-$  and water. When the protein-free fluid is filtered into the Bowman's capsule from the blood, it has the same osmo-concentration as the blood plasma of the capillaries surrounding uriniferous tubule. In the PCT,  $\text{Na}^+$  gets actively reabsorbed, and  $\text{Cl}^-$  gets reabsorbed passively as it is attracted to the positive charge of  $\text{Na}^+$ . 75 per cent of water of the filtrate simultaneously flows out of the PCT by osmotic effects of reabsorbed solutes. The volume of the filtrate thus falls by 75 per cent but it still remains isotonic to blood plasma.

The Henle's loop is largely responsible for concentrating the urine. It is found that the greater the ability of an animal to excrete hypertonic urine, the longer are the Henle's loops in its kidneys. Another factor in the concentration of urine is the presence of blood vessels called vasa rectae in the kidneys. The vasa rectae vessels are in the form of loops. So, the blood flows in opposite directions in the two limbs of each vasa recta; the blood entering its descending limb comes close to the outgoing blood in the ascending limb. This is called a COUNTER-CURRENT SYSTEM. Another counter-current system is constituted by two limbs of the Henle's loop. The glomerular filtrate flows in opposite directions in its two limbs. The filtrate entering its descending limb flows close to that leaving its ascending limb.  $\text{Na}^+$  and  $\text{Cl}^-$  are reabsorbed from the ascending limb into the surrounding medullary tissue where it is retained by the vasa rectae. Water cannot flow out of this limb as it is impermeable to water. Thus its contents become progressively more dilute (hypotonic). The walls of the descending limb are freely permeable to both salt and water. Thus, the reabsorbed

Birds cannot excrete urine as hypertonic as the mammalian urine. Reptiles cannot form hypertonic urine. Still, these animals can considerably reduce water loss in the urine, because their principal nitrogenous waste product happens to be insoluble uric acid. Their urine is stored in the cloaca along with the faeces. Large volume of water can then be reabsorbed from the urine in the cloaca, because uric acid does not osmotically hold back any water from reabsorption. Consequently, the urine volume ultimately becomes very little, just sufficient to sweep away the insoluble uric acid from the cloaca.

Camels are well known for their ability to withstand water-deprivation for long periods. But they do not store any water in the pouches of their rumen. The fat of hump is not particularly useful as a source of water because respiration must be enhanced to oxidise fat for producing water and this enhances respiratory loss of moisture. They doubtlessly reduce urinary water loss by secreting small volume of the urine much more hypertonic than the human urine; but it is still not so hypertonic as to explain their high tolerance of water-deprivation. But they lose far less water in the sweat, because they sweat only when their body temperature rises by as much as 6°C. Moreover, compared to all other mammals, they tolerate far higher water loss and far greater hemo-concentration. They can survive even after losing one-third of their body weight due to loss of body water; man dies if he loses one-fifth of his body weight due to water deprivation. These factors may be mainly responsible for the camel's ability to go without water for long periods.

Na<sup>+</sup> enters the descending limb from the surrounding fluid while water diffuses out of that limb and enters the surrounding tissue and thence into the capillaries surrounding the tubule (peritubular capillaries). The contents in the descending limb thus become hypertonic.

The permeability of the distal tubule and the collecting duct is under the control of a hormone released by the posterior pituitary called VASOPRESSIN or ANTIDIURETIC HORMONE (ADH). When the water content of the body is more than what it needs, the walls of the DCT and collecting tubule and collecting duct remain impermeable to water because ADH is not secreted in this condition. So, no water gets reabsorbed, but active reabsorption of Na<sup>+</sup> from the filtrate in these tubules

continues. The filtrate becomes more and more dilute and ultimately a large volume of hypotonic urine is eliminated.

When water content in the body is low and, therefore, has to be conserved, ADH is secreted from the posterior pituitary and makes the walls of the DCT, collecting tubule and collecting duct permeable to water. The surrounding tissue is hypertonic due to active reabsorption of Na<sup>+</sup> into it and due to the retention of Na<sup>+</sup> and urea by the counter-current system of vasa rectae. So, water is progressively reabsorbed from the filtrate flowing along the DCT, collecting tubule and collecting duct (rendered permeable by action of ADH) into the surrounding hypertonic tissue and the peritubular capillaries. The filtrate in the collecting duct consequently

becomes hyperosmotic and a strongly hypertonic urine flows out into the renal pelvis. regulation by eliminating either hypotonic or hypertonic urine, according to the need of the body.

The kidney thus helps in osmo-

## SUMMARY

Excretion is the elimination of waste products from the body. Lungs excrete carbon dioxide and some water in the expired air. But non-volatile solutes and water are mainly excreted in the urine. The urinary system consists of those organs of the excretory system which form, store and void urine.

A major function of the excretory system is the excretion of nitrogenous waste products. These are mainly produced by the catabolism of proteins. Animals are ammonotelic, ureotelic or uricotelic accordingly as they excrete ammonia, urea or uric acid as the principal nitrogenous waste product. Ammonotelic animals such as bony fishes, excrete mainly ammonia because they get enough water to dissolve the highly toxic ammonia and excrete it speedily. Ureotelic animals such as mammals and sharks cannot readily get as much water as is required for speedily excreting ammonia; so, they change ammonia to urea and excrete urea in the urine. Uricotelic animals such as birds and land reptiles have very limited access to water. So, they change ammonia to insoluble uric acid which may be swept out in the urine with the minimum amount of water.

The excretory system consists of organs and tissues participating in the excretion of waste products. In the *Hydra* and sponges waste products are excreted by diffusion from individual cells into the adjoining aqueous medium. Higher invertebrates and vertebrates have developed specialised tissues for excretion, e.g. nephridia in earthworms and Malpighian tubules in insects.

The mammalian urinary system consists of two kidneys which form the urine, two ureters which conduct the urine from kidneys to the urinary bladder, a urinary bladder for storage of urine and a urethra through which the urine is voided by bladder contractions. The kidney contains many minute tubular nephrons which are located partly in the renal cortex and partly in the renal medulla. They form urine and drain it ultimately into the pelvis of the kidney, from where the ureter arises.

The urethra is guarded by urethral sphincters. When enough urine accumulates in the bladder to raise its pressure sufficiently, the bladder wall contracts and urethral sphincters relax due to reflex. This brings about micturition. The act may also be initiated or delayed voluntarily.

Accessory excretory organs include the skin, lungs and liver. Skin excretes mainly water and sodium chloride in the sweat, and small amounts of lipids and sterols in the sebum. Lungs excrete carbon dioxide and some water vapour. Liver excretes bile pigments and cholesterol in the bile.

Each nephron starts from a blind expanded end called the Bowman's capsule, closely applied to a tuft of capillaries called the glomerulus. The Bowman's capsule is followed by a highly tortuous proximal convoluted tubule, a U-shaped Henle's loop,

a tortuous distal convoluted tubule and a collecting tubule. Collecting tubules drain the urine into collecting ducts. Collecting ducts open into ducts of Bellini which drain the urine into the renal pelvis.

The human urine contains water, urea, other nitrogenous waste products, sodium chloride, other mineral salts and some non-nitrogenous organic substances.

The urine is primarily formed by the filtration of a protein-free filtrate from the blood of glomerular capillaries into the Bowman's capsule. The force for forming this glomerular filtrate is provided by the difference between the blood pressure in the glomerulus and the sum of the osmotic pressure of plasma proteins and the capsular filtrate pressure. As the glomerular filtrate flows through the tubules, they reabsorb many substances from it. Some substances such as glucose, amino-acids and  $\text{Na}^+$  are reabsorbed actively and either largely or totally. Some other substances such as urea are absorbed in small amounts by diffusion. Water is absorbed passively by osmosis. Different portions of tubules absorb different substances. Tubules also secrete various substances such as  $\text{K}^+$ , uric acid, creatinine and ammonia into the urine. A combination of glomerular filtration, tubular reabsorption and tubular secretion forms the urine in nephrons.

Kidneys also maintain the osmotic concentration of blood and thus have a role in osmoregulation. This is largely due to counter-current mechanisms working in the kidney and the action of the antidiuretic hormone in promoting water reabsorption from the tubules.

## QUESTIONS

1. Match the items of column A with those of column B.

*Column A*

- (a) Ammonotelism
- (b) Bowman's capsule
- (c) Urinary bladder
- (d) Vasa rectae
- (e) Sebum
- (f) Uricotelism
- (g) Antidiuretic hormone
- (h) Tubular reabsorption
- (i) Ureotelism

*Column B*

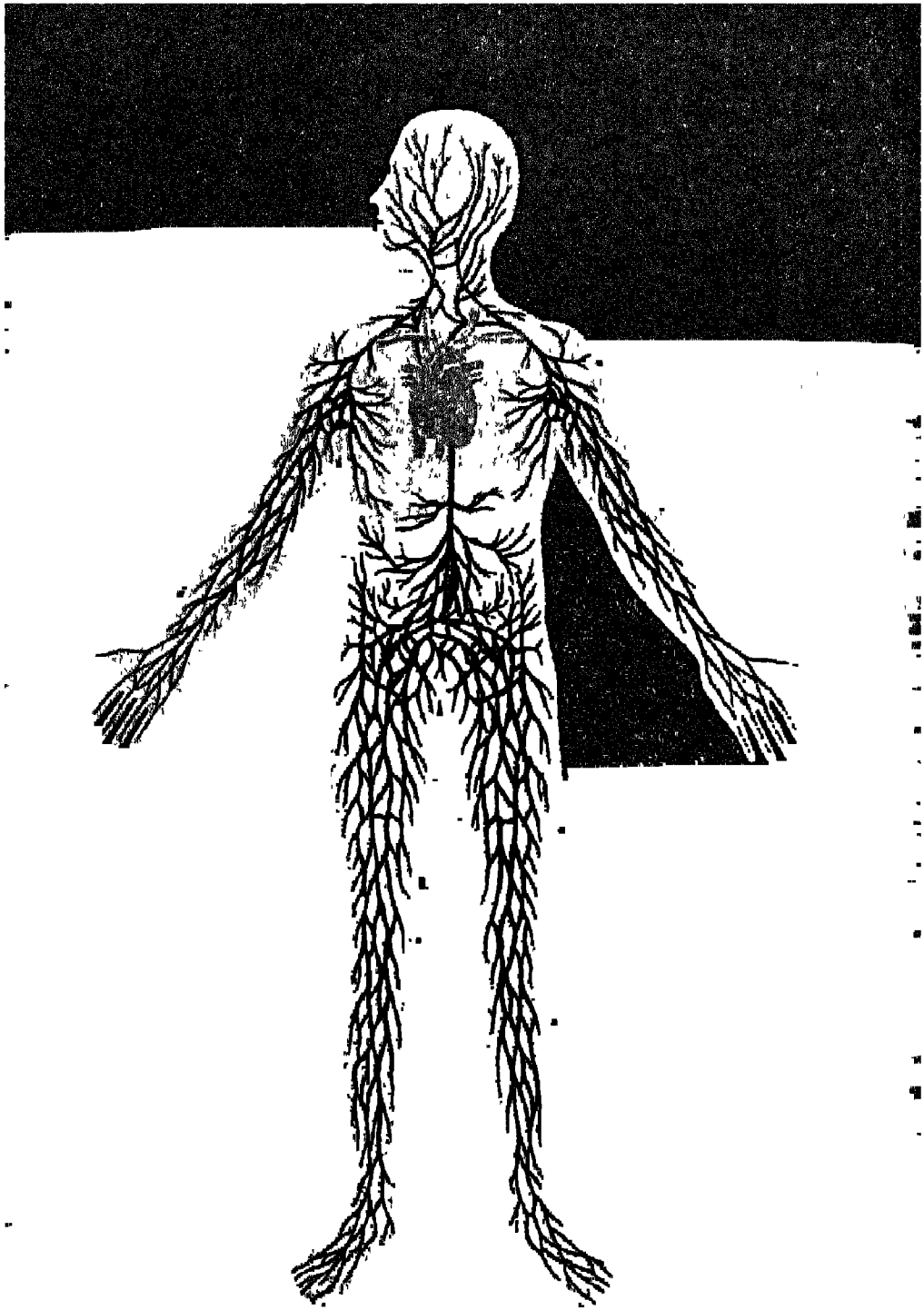
- (i) Birds
- (ii) Hypertonic urine
- (iii) Counter-current system
- (iv) Glucose
- (v) Glomerular filtration
- (vi) Micturition
- (vii) Flame cell
- (viii) Bony fish
- (ix) Skin
- (x) Shark

2. Indicate whether the following statements are true or false.

- (a) Micturition is carried out by a reflex.
- (b) The counter-current system of vasa rectae retain the reabsorbed  $\text{Na}^+$  in the medullary tissue.



- (c) ADH helps in water elimination, making the urine hypotonic.
  - (d) Protein-free fluid is filtered from blood plasma into the Bowman's capsule.
  - (e) Birds excrete ammonia as the principal nitrogenous end-product in the urine.
  - (f) Glucose is actively reabsorbed in the proximal convoluted tubule.
  - (g) Henle's loop plays an important role in concentrating the urine.
  - (h) Vasa rectae carry the glomerular filtrate from the distal convoluted tubule to the collecting duct.
  - (i) Urine reaches the bladder from the kidneys through the urethra.
3. Fill in the blanks with appropriate words:
    - (a) During micturition, the urinary bladder \_\_\_\_\_ and the urethral sphincters \_\_\_\_\_.
    - (b) Sweat serves to eliminate mainly \_\_\_\_\_ and \_\_\_\_\_.
    - (c) Blood enters the glomerulus through its \_\_\_\_\_ arteriole and leaves the glomerulus through its \_\_\_\_\_ arteriole.
    - (d) ADH increases \_\_\_\_\_ of \_\_\_\_\_ in the collecting duct.
    - (e) Two counter-current systems are formed in the kidney by the \_\_\_\_\_ and the \_\_\_\_\_.
    - (f) Name cells participate in excretion in animals like \_\_\_\_\_ while \_\_\_\_\_ possess Malpighian tubules as excretory organs.
    - (g) Cholesterol excreted in the \_\_\_\_\_ and waxes are excreted in the \_\_\_\_\_.
  4. Discuss how the kidney helps in osmoregulation in mammals.
  5. Describe the role of ADH and counter-current systems in forming hypertonic urine.
  6. Describe how urine is formed in the nephron through filtration, reabsorption and secretion.
  7. Explain the following:
    - (a) Skin functions as an accessory excretory organ.
    - (b) Mammals can eliminate hypotonic urine and hypertonic urine according to body needs.
    - (c) Micturition is reflex process, but is under some voluntary control.
    - (d) Mammals are ureotelic, but birds are obliged to be uricotelic.
    - (e) Different parts of a nephron participate in different ways in the formation of urine.
  8. Describe the structure of a nephron with a labelled diagram. + kidney
  9. Distinguish between
    - (a) Ureotelism and uricotelism.
    - (b) Sweat and sebum.
    - (c) Proximal and distal convoluted tubules.
    - (d) Ascending and descending limbs of Henle's loop.
    - (e) Tubular reabsorption and tubular secretion.
  10. Mark the odd one each of the following series.
    - (a) Renal pelvis, medullary pyramid, renal cortex.
    - (b) Afferent arteriole; Henle's loop; Vasa recta; efferent arteriole.
    - (c) Glomerular filtration; antidiuretic hormone; hypertonic urine; collecting duct.
    - (d) Proximal convoluted tubule; distal convoluted tubule; Henle's loop; renal corpuscle.



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## MOVEMENTS AND LOCOMOTION

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MOVEMENT is an important characteristic of living organisms. It takes mainly two forms in multicellular animals. One is LOCOMOTION. It is the act of walking, running, crawling, hopping, flying or swimming freely, either over a surface or in a liquid or gaseous medium. Locomotion distinguishes most animals from plants. It serves many purposes. It enables the animal to shift its entire body from place to place. In so doing, it transfers the animal from an unfavourable environment to a favourable one. It moves the animal away from predators. It helps the animal to search out and procure food and water. It also enables the animal to find its partner for reproduction and to reach favourable areas for egg laying or rearing of the young.

MOVEMENT OF BODY PARTS in relation to body axis is the other form of movement in animals. Such movements also serve many purposes. Movements of limbs, appendages, head and trunk serve to change the body posture to maintain equilibrium against gravity. Limb move-

ments are also required for carrying out locomotion. Prehension of food involves movements of tongue, jaws, snout, tentacles, limbs and appendages in different animals. Movements of eyeballs and pinna of ear help to collect information from the external environment. On the other hand, movements of the internal parts such as visceral organs, help in many biological activities by changing the volume and pressure in them. Food and urine are propelled by the movements of, respectively, digestive and urinary tracts. Cardiac movements circulate the blood. Lungs are ventilated by movements of thorax.

Besides locomotion and movements of body parts multicellular animals have retained in some of their cells many of the movements found in unicellular organisms. You may recall that ciliary, flagellar and amoeboid movements and cytoplasmic streaming take place in many unicellular organisms. In multicellular animals, phagocytes such as leukocytes and macrophages migrate through tissues by amoe-

roid movements. Ciliary movements of cells lining the upper respiratory tract, Fallopian tubes and vasa efferentia of testes transport, respectively, dust particles, ova and sperms in specific directions in those organs. Mammalian sperms move in the female reproductive tract by flagellar movements. Flagellar movements of cells lining the water canals in sponges maintain the water-current in those canals.

Locomotion and movements of multicellular animals depend mainly on the specialised cells endowed with the ability to contract. You may recall that muscle fibres are such contractile cells. Most multicellular animals possess muscles fibres for locomotion, limb movements as well as movements of internal organs.

In vertebrates, locomotion and limb movements are carried out by muscles in association with the skeletal system. The force generated by muscle contraction is utilised to move bones of the skeleton like levers. This results in movements of limbs and appendages. But there are also many invertebrates such as jelly fish, earthworm and leech, which are devoid of skeletons but possess muscles for their movements. Even in animals with the skeletal system, muscles of internal organs are not associated with any bone. Such muscles are either smooth muscles or cardiac muscles while muscles working with the skeletal system are called SKELETAL MUSCLES. Movements in some invertebrates are briefly described below.

#### Movements in Hydra

The muscle fibres are lacking in *Hydra*. Instead, the animal has two types of contractile cells on its body wall, viz. epitheliomuscular cells in the outer layer of the body wall and the nutritive muscu-

lar cells in the inner layer (Fig. 35.2). Processes of these cells run in the body wall both along the long axis of the body and around the central body cavity. Contractions and relaxations of these cells, respectively, shorten and elongate their processes. They consequently cause all sorts of movements of *Hydra* including shortening, elongation and bending of the body and tentacle movements. Locomotion is carried out by somersaults and looping (Fig. 37.1).

#### Movements in Annelids

Annelids such as earthworms and leeches possess muscle fibres on the body wall, some running circularly around the body and others coursing along its long axis. But they do not possess any skeletal system. Instead, the muscular movements push their blood in the direction of propagation. This movement of the blood serves to move the animal forward. Crawling movements in leech are shown in Fig. 37.2.

#### Movements in Starfish

Starfishes utilise a flow of water for crawling over a surface. Each arm of the starfish bristles below with two rows of TUBE-FEET. Muscular contractions drive water into them from the water canals of the animal body. This flow of water moves the tube-feet, carrying the animal over the surface of the substratum (Fig. 37.3).

#### Movements in Higher Vertebrates

##### The Skeletal System

In higher animals, movements and locomotion depend on the association of skeletal muscles with the skeletal system. The latter consists of bones, a specialised rigid connective tissue. Bones have great tensile

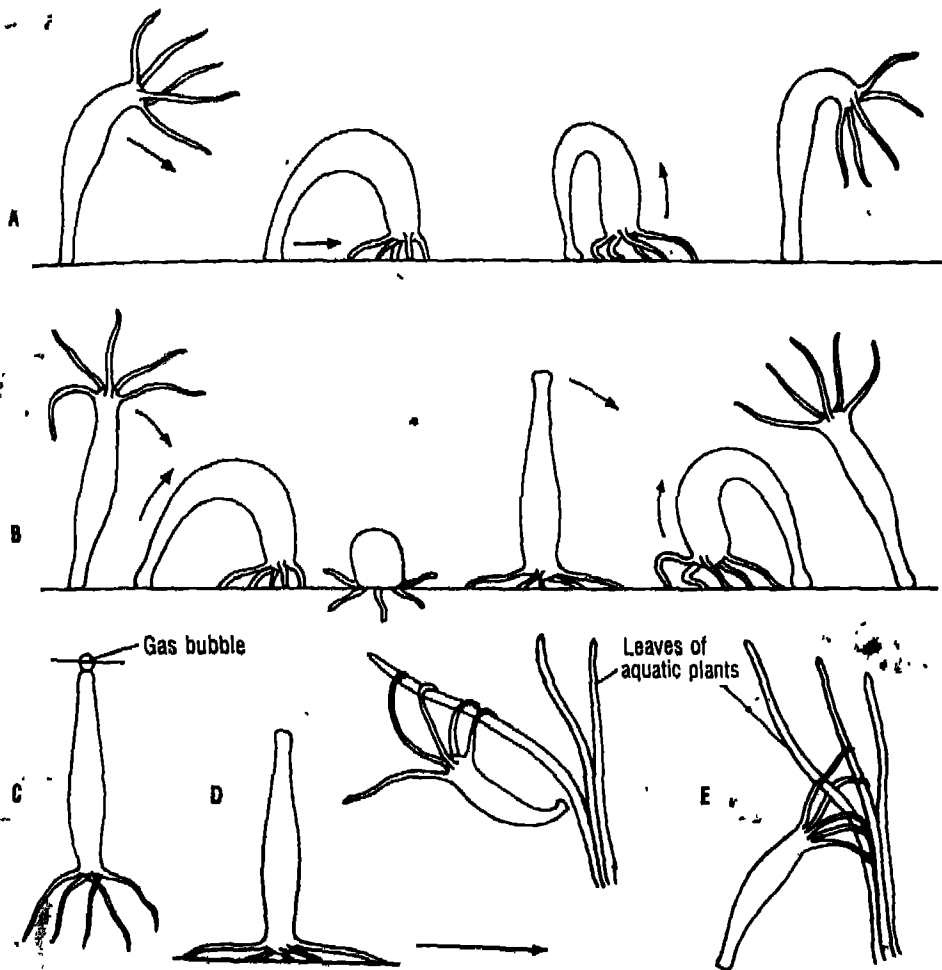


Fig. 37.1 Locomotion in *Hydra*: A. Looping; B. Somersault; C. Floating; D. Inverted movement and E. Climbing. (Arrows indicate the direction of body movements)

strength, almost as high as that of cast iron. The skeletal system consists of many parts, each made of one or more bones.

According to the shape and size, bones are categorised as long, short, flat and irregular bones. The thigh bone (femur) and

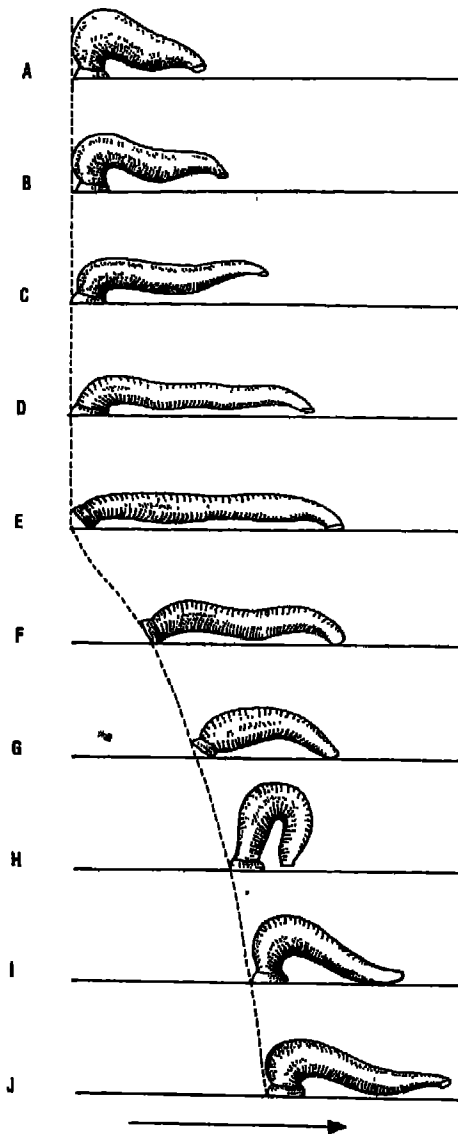
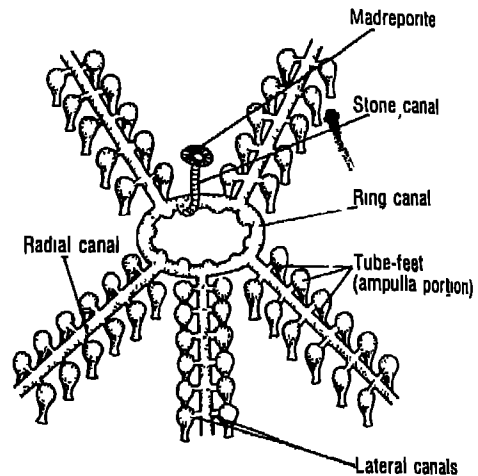


Fig. 37.2 The characteristic movement of leech on a substratum through contraction and relaxation of muscles of the body wall. A to J—Different stages of movement



*Femur: longest bone*

Fig. 37.3 Water vascular system in a starfish (diagrammatic) showing water canals and tube-feet

the bone of the upper arm (humerus) are examples of long bones. The breast bone (sternum) and the shoulder blade (scapula) are flat bones. Vertebrae are irregular bones. Some major parts of human skeleton consist of the following numbers of bone—skull or cranium : 8, face : 14, each forelimb : 30, each hindlimb : 30, vertebrae : 24, sacrum : 1, coccyx : 1, sternum : 1, ribs : 24, pelvis : 3, each shoulder girdle : 2 (Fig. 37.4). The skeleton contains a total of 206 bones in man.

The skeletal system performs the following functions:

1. It forms the rigid structural framework of the body and supports the weight of

# MOVEMENTS AND LOCOMOTION

Flat bones - Sternum,  
 Scapula  
 Irregular - Vertebrae  
 Skull - 8, Face - 14  
 Forelimb, hindlimb - 30, 30  
 Shoulder girdle - 2

Long bone - Femur,  
 humerus<sup>651</sup>  
 vertebrae - 24  
 Sacrum - 1  
 coccyx - 1  
 Sternum - 1  
 ribs - 24  
 pelvis - 3

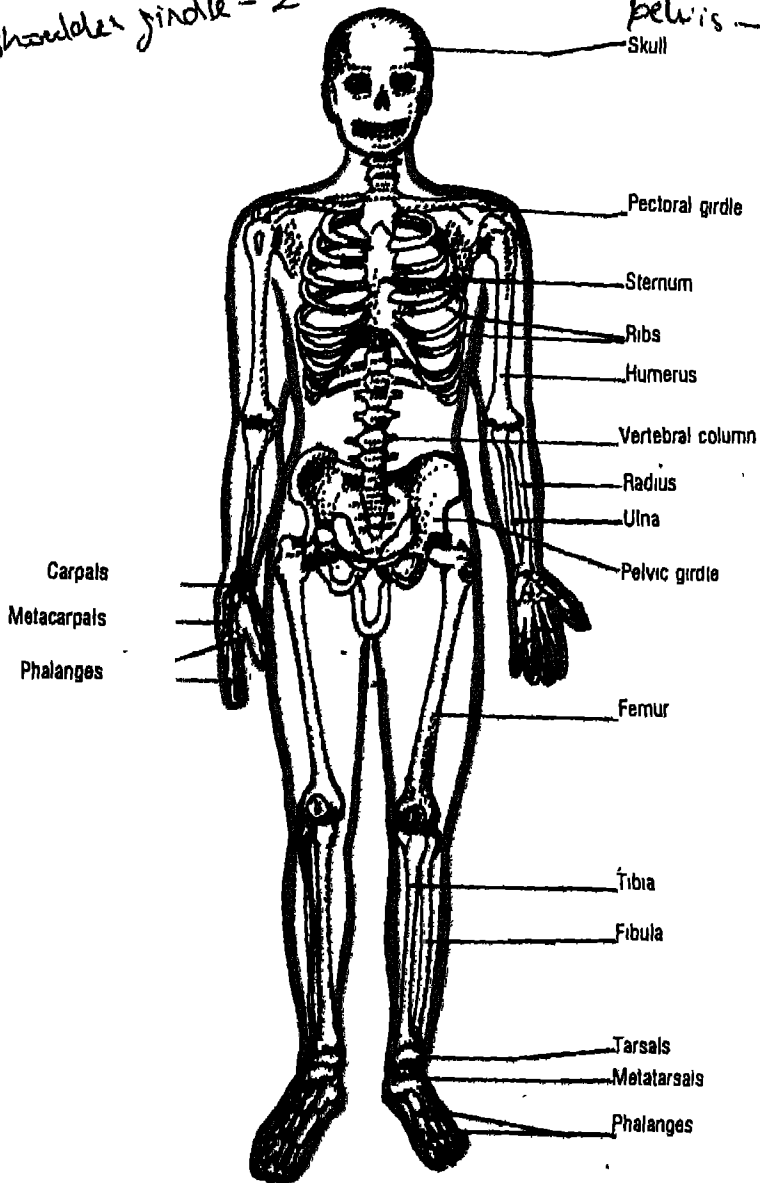


Fig. 37.4 The articulated skeleton of man. It is made up of 206 pieces of bones.

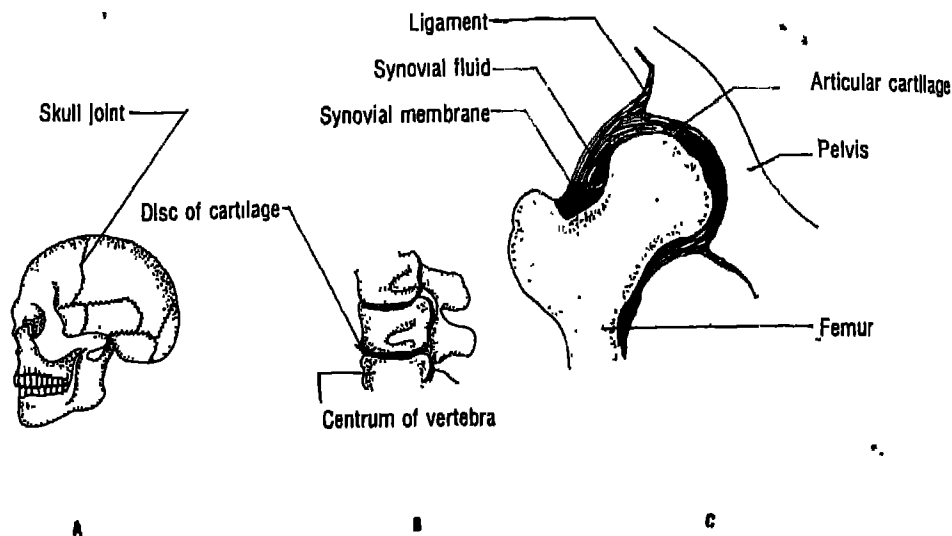


Fig 37.5 Types of joints: A. Fixed joints of skull bones; B. Cartilaginous joints (between vertebrae) and C. Synovial joint (between pelvic girdle and femur)

- the body along with its limbs. This weight-bearing function of the skeletal system depends on the deposits of calcium and phosphate in the matrix of bone tissue.
2. It affords protection to internal organs against mechanical injury by forming cage-like compartments, e.g. skull is made up of several small bones and protects brain, eyes, ears and mouth cavity.
  3. It serves as a storage depot for calcium and phosphate, which are released for several functions of the body.
  4. It participates in movements and locomotion. The ends of each skeletal muscle are inserted into more than one

bone by means of strong, dense and flexible connective tissue bands called TENDONS.

5. It carries the tissues for the formation of the blood cell. Both the erythrocytes and leukocytes are produced in the red bone marrow present in the interstices of the spongy bones of vertebrae, sternum, scapula and in the ends of long bones, such as humerus, femur.

Joints: Joints are structures where two bones are fitted to each other. The surfaces of the two bones are in apposition to each other at the joint. In many cases, these articulating surfaces also move upon each other at the joint. Because



## MOVEMENTS AND LOCOMOTION

bones articulate with each other in this way at the joints, a bone is moved at the joint by the contraction of a muscle inserted into that bone. Movements of the skeletal system thus occur actually at the joints.

According to the mobility of joints, they are classified into fixed, slightly movable and freely movable joints (Fig 37.5). Their mobility depends on their structure. At FIXED OR FIBROUS JOINTS, the articulating bones are firmly held together by dense bands of tough, inextensible white fibrous tissue. These joints permit no movement of the articulating bones, e.g. sutures of skull bones. At SLIGHTLY MOVABLE OR CARTILAGINOUS JOINTS such as those between vertebrae and at the symphysis pubis, a dense disc of white fibrocartilage joins the opposing surfaces of the articulating bones to each other. This allows a limited movement at the joint. You must be aware that some bending and a little rotation of the vertebral column are possible, but its movements are far less than those at the knee or shoulder joints. The latter are examples of FREELY MOVABLE OR SYNOVIAL JOINTS where the articulating bones can move extensively upon each other. Here, the articulating surface of each bone is covered with a smooth piece of hyaline cartilage. A viscous slippery SYNOVIAL FLUID fills the space between these cartilages and lubricates the joint for easy bone movements. The articulating surfaces are kept in close contact by a fibrous capsule.

Synovial joints are further classified according to the movements they permit. BALL-AND-SOCKET JOINTS are the most mobile of all synovial joints (Fig. 37.6). The spheroidal ball-like end of one bone articulates here with the cup-shaped depression in another. This allows the

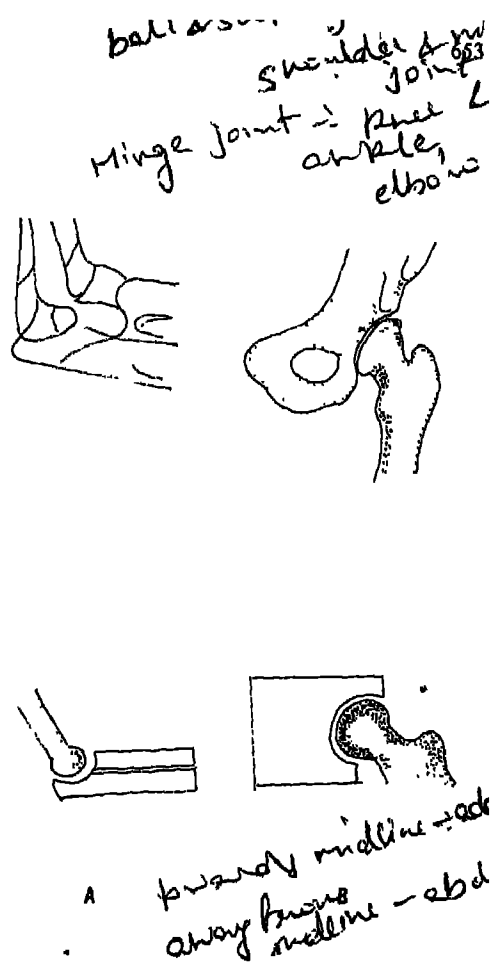


Fig. 37.6 A. Hinge joint and B. Ball-and-socket joint

bone with the ball head to be moved freely in many planes. Shoulder joints and hip joints are the ball-and-socket joints (Fig 37.6). Movements at such joints may stretch (extend), fold (flex) and rotate a limb, they may also draw a limb towards the body midline (adduct), and move it away (abduct) from the latter. HINGE JOINTS closely resemble the hinges which hang a door from the side post of the door-frame. The ankle, knee and elbow joints are hinge joints (Fig 37.6). They permit movements in a single plane only. PIVOT JOINTS permit only movements resembling the rotation of a body around a

<sup>bones</sup>  
gliding = bones of palm  
Ellipsoidal = toe, sole & foot (two axes)

pivot. The upper ends of the forearm bones articulate with each other in a pivot joint. Their articulating ends may be rotated around a single axis passing through that joint. The articulating surfaces of two bones glide over each other at GLIDING JOINTS. Such joints include those between some of the bones in the palm of in the sole of foot. ELLIPSOID JOINTS permit movements of articulating bones around two axes. Such joints are formed between the toe bones and some bones in the sole of foot.

Movements are produced at joints by contractions of skeletal muscles inserted into the articulating bones. Flexible connective tissue bonds called LIGAMENTS stabilise the joints by holding the articulating bones together.

### *Movements of Skeletal Muscles*

The skeletal muscles are made of striated muscle fibres and are under voluntary control. The skeletal muscles are frequently categorised to indicate the movements brought about by them in the body. For example, the contraction of a FLEXOR folds up a joint by drawing one of the articulating bones to the other; this causes a folding or flexion of the limb where the joint is located. The contraction of an EXTENSOR extends a joint by pulling one of the articulating bone apart from another; this causes a stretching or extension of the limb. The contraction of a PRONATOR rotates the forearm to turn the palm downward or backward.

A SUPINATOR contracts to rotate the forearm and thus to make the palm face upward or forward. An ABDUCTOR contracts to draw a bone away from the body midline while an ADDUCTOR draws a bone towards the body midline. The muscles which contract to produce opposite move-

Arthritis or inflammation of a joint makes the joint painful and may even immobilise the movements at the joint. This may result from a lack of the synovial fluid at the joint, the ossification of the articular cartilage, deposition of uric acid crystals in the joint cavity, or other changes at the joint.

Slipped disc is a displacement of vertebrae from their normal positions in the vertebral column. It may arise from causes like mechanical injury and defects of ligaments holding the vertebrae together. The articulating surfaces of the affected vertebrae are no longer properly apposed to each other. Nor is the disc of fibrocartilage between vertebrae in proper alignment with the articulating vertebrae.

ments at the same joint, are called ANTAGONISTIC MUSCLES. When a muscle contracts to produce a movement, its antagonist must relax to allow that movement to take place. The biceps is a flexor for the elbow joint, and the triceps is its antagonist and an extensor for that joint. During flexion at the elbow, biceps contracts and triceps relaxes; during extension at the same joint, triceps contracts and biceps relaxes.

Threshold Stimulus: Each skeletal muscle is composed of many muscle fibres. The contraction or shortening of a muscle results from the contraction of its muscle fibres. Each muscle fibre is supplied by a nerve. The latter conducts propagated changes of electrical potentials called NERVE IMPULSES to the muscle fibre.

When the nerve fibre reaches a nerve impulse of adequate strength to the muscle fibre, the latter is stimulated and responds by contracting or shortening. When the muscle fibre is not stimulated by any nerve impulse, it relaxes and remains limp. Besides nerve impulses, the muscle fibre may be stimulated by adequate strengths of electrical, mechanical, chemical or other forms of stimuli also. But for being stimulated to contract, the muscle fibre always requires a specific minimum strength or intensity of the stimulus or nerve impulse. This is called THRESHOLD STIMULUS of the muscle fibre and it differs from fibre to fibre even in

the same muscle. If the nerve impulse or any other stimulus is below its threshold intensity, it fails to stimulate and contract the muscle fibre.

Single Twitch and Tetanus: A muscle fibre contracts only once if it is stimulated by a single nerve impulse or electric shock of adequate strength. This single isolated contraction of the muscle fibre is called MUSCLE TWITCH. Immediately after the brief twitch, the muscle fibre relaxes. But if a muscle fibre is stimulated by a rapid succession of many nerve impulses or electric shocks, it remains in a state of sustained contraction so long as the stimulation continues. Such a continued state of

*tetani*

#### ALL-OR-NONE LAW

On being stimulated, each muscle fibre contracts with the maximum force if it contracts at all. If the stimulus is of a strength below the threshold, it fails to stimulate the muscle fibre and the latter does not contract at all. But if the stimulus has a strength equal to or higher than the threshold stimulus, the muscle fibre always contracts with the maximum force irrespective of the strength of the stimulus; the force of contraction does not rise in such a case on increasing the strength of the stimulus. This is known as ALL-OR-NONE LAW. Even with the same strength of stimulus, however, the force of contraction may rise on changing other conditions like a change in temperature or pH or a slight stretching of the fibre. But even under such a changed condition, the force of contraction cannot be increased by enhancing the strength of stimulus. The all-or-none law is obeyed by not only striated muscle fibres, but also cardiac and smooth muscle fibres and nerve fibres. The force of contraction of a muscle depends on the force and number of the contracting muscle fibres in it. With the rise in the strength of stimulus, the muscle as a whole increases its force of contraction. In other words, the entire muscle does not obey the all-or-none law although all its muscle fibres individually obey that law. This can be explained by the fact that the strength of the threshold stimulus varies from muscle fibre to muscle fibre in a muscle. A weak stimulus can stimulate only a few fibres which have low thresholds, but a stronger stimulus succeeds to stimulate a larger number of fibres by stimulating even those with high thresholds. Each of the fibre contracts maximally whenever it contracts. But as the number of contracting muscle fibres increases with the strength of stimulus, the force of contraction of the muscle as a whole increases with the rise in stimulus strength.

contraction is called TETANUS. Much higher tension is developed in a tetanus than in an isolated twitch. Almost all our daily activities are carried out by tetanic contractions of muscles.

### Mechanism of Muscle Contraction

You may recall that each myofibril of a striated muscle fibre contains thin actin filaments and thick myosin filaments. These filaments are arranged longitudinally inside the light I bands and the dark A bands, respectively. The actin and myosin filaments remain cross-linked with each other in the myofibril. Each myofibril consists of a row of functional units called sarcomeres, each extending from the fine dark Z line or band at the middle of one I band to the Z line of the next I band (Fig. 37.7). Each sarcomere consists, therefore, of an A band in the middle with halves of two I bands on its two sides. From each Z line, the actin filaments extend through the half of the I band and interdigitate with the ends of myosin filaments in the A band. The myofibril is encircled at each I band by the cisternae and tubules of sarcoplasmic reticulum, and at each junction of A and I bands by a T tubule communicating with the cell exterior.

According to SLIDING FILAMENT THEORY of muscle contraction, the actin filaments slide over the myosin filaments to penetrate deeper into the A bands in the contracting muscle fibre. This results from a breakage and rearrangement of the cross-linkages between actin and myosin filaments. When the muscle fibre is stimulated, the ATP is broken by the ATPase activity of myosin molecules. The cleavage of ATP provides the energy for an interaction between actin and myosin filaments. This causes a rearrangement of

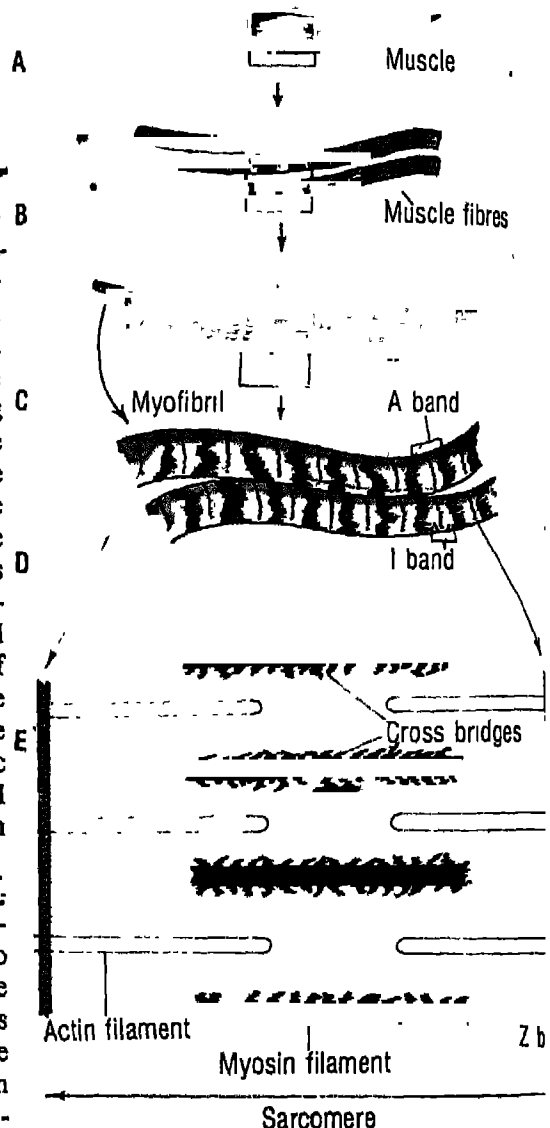


Fig. 37.7 Structure of muscle as revealed under the light and electron microscopes

the cross-linkages between the filaments. In consequence, the thin actin filaments slide deeper into the A band between the thick myosin filaments (Fig. 37.8). The Z line, limiting the sarcomere, are drawn closer together by the sliding actin filaments. This shortens the sarcomere; as all the sarcomeres of the myofibril are shortened simultaneously, the myofibrils and consequently the muscle fibre shorten on contraction. Because the actin filaments of the I band pass deeper into the A band, the I bands are reduced considerably in length; but the A bands continue to remain unchanged in length. In other words, the sarcomere shortens because of the shortening of its I bands. During relaxation, the cross-linkages between the filaments are rearranged again and the actin filaments slide out from the A band. This elongates the I bands, pushes the Z line away from each other and, consequently, lengthens the myofibril as well as the muscle fibre.

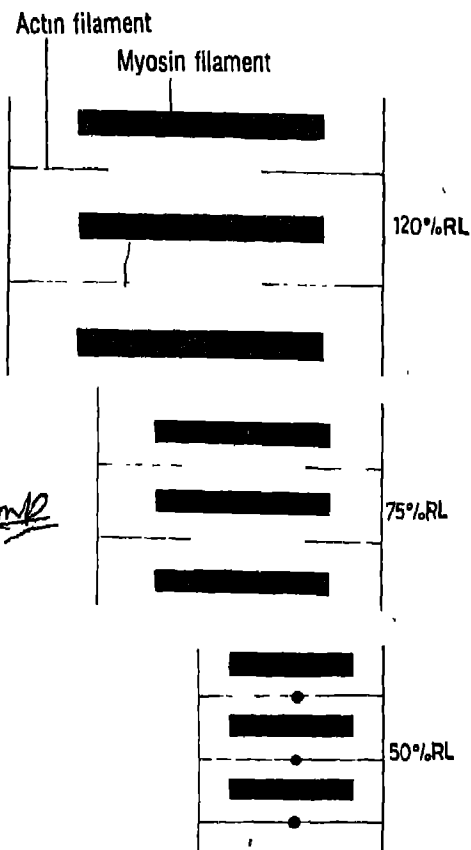


Fig. 37.8 A diagrammatic illustration explaining the sliding filament theory (RL = Relaxed length)

#### Chemical Changes in Muscle Contraction

You may recall that ATP is the immediate source of energy for muscle contraction. So, the most important chemical change in the contracting muscle is the hydrolysis of ATP to ADP and inorganic phosphate by myosin ATPase:



To continue muscle contraction, ATP is immediately replenished in the muscle fibre. For the prompt restoration of ATP, the muscle fibre contains another high-energy compound called creatine phosphate. ADP reacts with the latter to produce ATP and creatine:  $\text{ADP} + \text{creatine phosphate} \rightarrow \text{ATP} + \text{creatine}$ .

Although ATP is replenished, creatine phosphate decreases in the contracting muscle. However, during recovery immediately after contraction, creatine is

reconverted to creatine phosphate by the reverse reaction utilising ATP generated by carbohydrate oxidation:  $\text{ATP} + \text{creatine} \rightarrow \text{ADP} + \text{creatine phosphate}$ . During muscle contraction, carbohydrates are metabolised through glycolysis in the muscle to produce ATP. This results in the formation of lactic acid from carbohydrates. During recovery after contraction, lactic acid is oxidised to carbon dioxide and water aerobically, giving more energy.

#### Fatigue

On being repeatedly stimulated to con-

### OXYGEN DEBT

During strenuous exercise, the muscle does not get sufficient oxygen to meet its energy needs immediately. So, it contracts anaerobically and accumulates lactic acid produced by anaerobic glycolysis. During recovery, the oxygen consumption of the muscle far exceeds that in the resting state. The extra oxygen consumed during recovery is called OXYGEN DEBT of the muscle. It is used in oxidising the accumulated lactic acid aerobically and in restoring the depleted creatine phosphate and ATP in the muscle fibre. A small part of the oxygen debt also goes to supply oxygen to myoglobin which binds and stores oxygen for future use. Athletic training enhances the capacity for aerobic contractions. So, athletes incur far less oxygen debts during strenuous exercise than non-athletes.

tract, the muscle fibres take progressively longer time to respond to the excitation, to develop tension during contraction and also to complete relaxation. Their force of contraction also declines progressively. Ultimately, the fibres fail to contract at all for some time. This is known as FATIGUE of the muscle fibres. It is caused by the accumulation of lactic acid and other changes in the muscle due to prolonged contractions. On being allowed to rest for some time, the fatigue is removed and the muscle can contract again.

### Red and White Muscle Fibres

The mammalian and avian skeletal muscles contain two major types of striated

muscle fibres. Some of the muscle fibres are thinner, darker in colour and slower in contraction rates. They are called SLOW OR RED MUSCLE FIBRES. Their dark red colour is due to the presence of the red heme-protein called myoglobin. It binds and stores oxygen as oxymyoglobin in the red fibres. Oxymyoglobin releases oxygen for utilisation during muscle contraction. In addition, the red muscle fibres are very rich in mitochondria. Both these factors enable them to carry out considerable aerobic oxidations. Because they produce energy mainly by aerobic metabolism, they carry out aerobic contractions without accumulating much lactic acid. So, the red muscle fibres can go on contracting for prolonged durations without fatigue. The muscles which perform sustained work at a slow rate over a prolonged interval, are made mostly or wholly of the red muscle fibres. Extensor muscles on the back of the human body are very rich in the red muscle fibres; these muscles continue in sustained contraction for maintaining the erect posture against gravity. Some avian flight muscles are red muscles; birds use these muscles for prolonged slow flying like the sailing of kites in the air.

The striated muscle fibres of a second type are much thicker, lighter in colour, poorer in mitochondria, free of myoglobin and faster in contraction rates. They depend mainly on anaerobic glycolysis for energy production. So, they carry out anaerobic contractions, accumulate lactic acid in considerable amounts during strenuous work and soon get fatigued. These are known as WHITE OR FAST-MUSCLE FIBRES. They are specialised for very fast and strenuous work for a short interval. The muscles which perform fast and strenuous work for short intervals, are made mostly or wholly of the white mus-

## MOVEMENTS AND LOCOMOTION

cle fibres. The muscles for eyeball movements are very rich in white fibres. The muscles are like that of a sparrow, are white. The avian flight muscles, used in short fast fly-

### SUMMARY

Animals possess two forms of movements—locomotion and movements of body parts. Locomotion transfers the animal to more favourable environments. Movements of body parts help to maintain body posture, to collect information, to carry out prehension of food and to perform the activities of internal organs. Most animals have developed contractile muscle fibres for carrying out movements. In many animals, muscle contractions move bones of the skeleton like levers to produce body movements. But many invertebrates lack the skeletal system.

Locomotion of *Hydra* consists of movements resulting from contractions of epitheliomuscular and nutritive muscular cells in its body wall. In earthworms and leeches, muscular movements push the blood in the direction of propagation. This movement of blood serves to move the animal forward. In starfishes, muscular contractions drive water from their water canals to their tube-feet which consequently move to carry the animal over a surface.

In higher animals, the skeletal system participates in movement and locomotion in association with the skeletal muscles. It also forms a supporting framework for the body, protects its softer internal organs, stores calcium and phosphorus, and houses the red bone marrow where the blood cells are formed.

Bones articulate with each other at joints. Muscular contractions move the bones at the joints. At fixed or fibrous joints, the articulating bones are firmly held together by the white fibrous tissue so that the bones are not allowed to move at such joints. At slightly movable or cartilaginous joints, the opposing surfaces of the articulating bones are joined by white fibrocartilage, allowing a limited movement at the joint. At freely movable or synovial joints, a slippery synovial fluid occurs in the space between the articulating surfaces of bones; its lubricating action permits considerable movements at such joints. The synovial joints are classified into ball-and-socket joints, hinge joints, pivot joints, gliding joints and ellipsoid joints according to the movements they permit.

The skeletal muscles are categorised into flexors, extensors, pronators, supinators, abductors and adductors according to the movements they bring about. The muscles which contract to produce opposite movements at the same joint are called antagonistic muscles. When a muscle contracts to produce a movement, its antagonist must relax to allow that movement.

For being stimulated, each muscle fibre requires a specific minimum intensity of nerve impulse or stimulus. This is called its threshold stimulus. A sub-threshold stimulus fails to cause any contraction of the muscle fibre.

A single isolated contraction, caused by a single nerve impulse or electric shock, is called a muscle twitch. A continued state of contraction caused by many rapidly repeated stimuli, is called a tetanus.

When the muscle is stimulated, thin actin filaments of I bands slide over the thick myosin filaments to penetrate deeper into the A bands; the I bands as well as the sarcomeres shorten as a result, causing the muscle fibre to shorten also. This is the sliding filament theory of muscle contraction. During relaxation, actin filaments slide out again from the A bands, elongating the sarcomeres.

During muscle contraction, ATP is hydrolysed to ADP to provide the required energy. It is promptly resynthesised from ADP by reacting the latter with creatine phosphate. But replenishment of ATP ultimately depends on the oxidation of glycogen and glucose in the muscle fibre. During muscle contraction, carbohydrates are broken down by anaerobic glycolysis, causing lactic acid to accumulate in the muscle. During recovery after contraction, the accumulated lactic acid is oxidised aerobically in the muscle fibre. On repeated contraction, the muscle fibre undergoes fatigue due to the accumulation of lactic acid and other changes in it.

Red or slow muscle fibres are rich in mitochondria and contain myoglobin which stores some oxygen for use during contraction. They depend mainly on aerobic metabolism. This enables them to perform slow and sustained contractions for prolonged periods without fatigue. White or fast muscle fibres are poorer in mitochondria, contain no myoglobin and mainly depend on anaerobic glycolysis. They specialise in fast and strenuous work for short intervals. Muscles such as antigravity extensor muscles are richer in red muscle fibres. Muscles for eyeball movements are richer in white muscle fibres.

## QUESTIONS

1. Distinguish between:

- (a) Pronator and supinator.
- (b) Muscle twitch and tetanus.
- (c) Ball-and-socket joint and hinge joint.
- (d) Abductor and adductor.
- (e) Tendon and ligament.
- (f) Fixed joint and synovial joint.
- (g) White muscle fibre and red muscle fibre

2. Match the items of Column A with those of Column B:

### Column A

- (a) Fixed joint
- (b) Fast muscle fibres
- (c) Tube-feet
- (d) Scapula
- (e) Slow muscle fibres
- (f) Actin filament
- (g) Epitheliomuscular cell
- (h) Freely movable joint
- (i) Sarcomere
- (j) Cartilaginous joint

### Column B

- (i) Myoglobin
- (ii) Synovial fluid
- (iii) Vertebrae
- (iv) *Hydra*
- (v) Lactic acid
- (vi) Z band
- (vii) I band
- (viii) T tubules
- (ix) Sutures of skull
- (x) Flat bone
- (xi) Starfish



3. Explain the following terms:

- (a) Antagonistic muscles (b) Tetanus (c) Threshold stimulus (d) Sarcomere (e) Fatigue (f) Muscle twitch

4. Mark the wrong item in each of the following series:

- (a) Sarcomere; actin filaments; myosin filaments; sarcoplasmic reticulum.  
(b) Pronator; ligament; adductor; supinator.  
(c) Hip joint; knee joint; ankle joint; elbow joint.  
(d) Shoulder joint; toe joint; ankle joint; intervertebral joint.

5. Answer the following briefly:

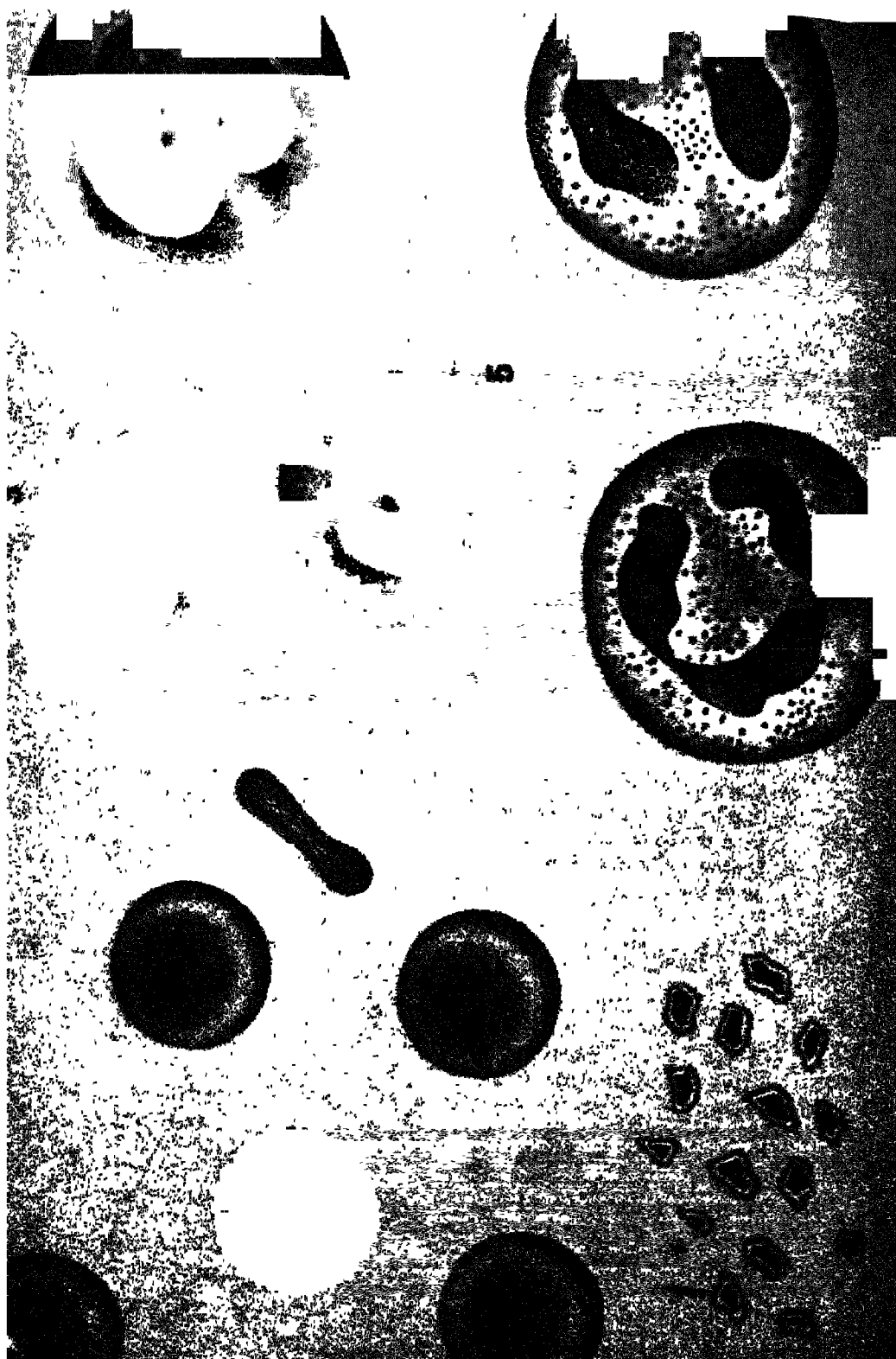
- (a) How does the muscle shorten during its contraction and lengthen during its relaxation?  
(b) What biological functions are served by the skeletal system?  
(c) What types of muscle will be antagonistic to pronators and abductors respectively, and why?  
(d) Why a red muscle fibre can work for a prolonged period while a white muscle fibre suffers from fatigue after a shorter work?  
(e) Where from the muscle gets energy for its contraction?

6. Write briefly the biological importance of the following:

- (a) Myoglobin (b) Actin and myosin filaments (c) Synovial joints (d) Fibrous joints  
(e) Lactic acid.

7. Fill in the blanks with correct words:

- (a) The skull bones are joined at the sutures by \_\_\_\_\_ tissue while the bodies of vertebrae are joined by \_\_\_\_\_ tissue.  
(b) A \_\_\_\_\_ muscle rotates the forearm to turn the palm downward while a \_\_\_\_\_ muscle rotates the forearm to turn the palm upward.  
(c) \_\_\_\_\_ muscle fibres store much oxygen in combination with \_\_\_\_\_.  
(d) Contraction of a \_\_\_\_\_ muscle draws a limb towards the body midline while contraction of a \_\_\_\_\_ muscle draws a limb away, from the body midline.  
(e) During the flexion of the elbow joint, the \_\_\_\_\_ muscle contracts while the \_\_\_\_\_ muscle relaxes.



## CONTROL AND COORDINATION NERVOUS SYSTEM

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WITH the evolution of multicellularity, it became imperative to develop some system for coordinating the activities of numerous cells in the body. For such coordination, information has to be exchanged between cells situated at a distance from each other; information has also to be received about changes in the external environment and then transmitted to the cells not immediately near the site of change. For coordination of other systems, the nervous system and the endocrine system have been developed. The first is made of neurons which act by conducting nerve impulses. The second consists of endocrine glands which secrete hormones into the blood. This chapter is devoted to the coordinating functions of the nervous system; the endocrine system discussed in the next chapter.

The nervous system serves its coordinating role in several ways. It receives information of changes in the external environment and analyses and interprets the information to produce sensations,

like vision and pain. It forms and retains the memory of past information on its background for interpreting future information. It conducts information and messages between different parts of the body. It stimulates or inhibits the activities of the muscles and glands to evoke responses to the received information. It also receives information of changes in the interior of the body and coordinates the activities of visceral organs in the light of those changes; thereby, it helps to maintain the constancy of the internal environment in the body. Special senses such as vision, hearing, smell and taste are produced by the information received by the sense organs like eyes and ears, associated with the nervous system.

In mammals, the nervous system consists of the central nervous system, peripheral nervous system and autonomic nervous system. The central nervous system comprises the brain and the spinal cord. The peripheral nervous system includes nerves coursing between the central nerv-

ous system and different parts of the body.

The autonomic nervous system has connections with the central nervous system but works somewhat independently to regulate the involuntary activities like heart beat, peristalsis of intestine, etc.

### **The Central Nervous System (CN System)**

The central nervous system consists of the brain and the spinal cord. The areas of the CN system where the cell bodies of the neurons are situated, look grey and constitute the grey matter. Other areas look white and constitute the white matter of the CN system. The white matter contains only nerve fibres cruising from or to the nerve cells in the grey matter. It looks white due to the presence of myelin around the myelinated fibres.

Both the brain and the spinal cord are covered by three connective tissue membranes. These are called pia mater, arachnoid mater and dura mater, respectively, from within outward. Together they are known as meninges. An extracellular fluid, called CEREBROSPINAL FLUID occurs in the subarachnoid space between the pia and arachnoid matters. It also occupies the lumens of several intercommunicating cavities, called cerebral ventricles inside the brain and the spinal canal running along the centre of the spinal cord. It affords some protection to the CN system against mechanical injury and shock. The exchange of materials between it and the neurons help in their nutrition and excretion. The cerebrospinal fluid serves to maintain a constant pressure inside the cranium in spite of fluctuations in the volume and pressure of blood in the cranial vessels.

### **Brain**

The brain is situated inside the cranium, the bones of which protect it from injuries. The human brain may be divided into forebrain, midbrain and hindbrain. The hindbrain continues into the spinal cord.

In most parts of the brain, the grey matter containing the nerve cells is situated on the surface while the white matter made of fibres is located deep inside the brain.

The forebrain consists of the cerebrum, the largest part of the human brain (Fig. 38.1). The cerebrum consists of two cerebral hemispheres joined by a curved thick band of nerve fibres, called CORPUS CALLOSUM. Three deep and wide fissures divide each cerebral hemisphere into frontal, parietal, temporal and occipital lobes. CEREBRAL CORTEX is the outer layer of the cerebrum. It is made of grey matter and contains many layers of nerve cells. The nerve cells of different areas of the cerebral cortex differ in size, shape and functions; for example, the conical-shaped, pyramidal cells of the motor area of the cortex give rise to efferent fibers for controlling the skeletal muscle movements. The surface of each cerebral hemisphere shows many convolutions called GYRI (singular: GYRUS) separated by depressions, called sulci. The gyri increase the surface area of the cortex for accommodating far more nerve cells in it.

The cerebral cortex is the highest centre for many sensations and activities (Fig. 38.2). The general sensory or SOMAESTHETIC AREA in the parietal lobe is the seat for perception of general sensations like pain, touch and temperature. The motor area in the frontal lobe controls the voluntary movements of the muscles. The PREMOTOR AREA in the frontal lobes is the highest centre for involuntary movements of the muscles and for the

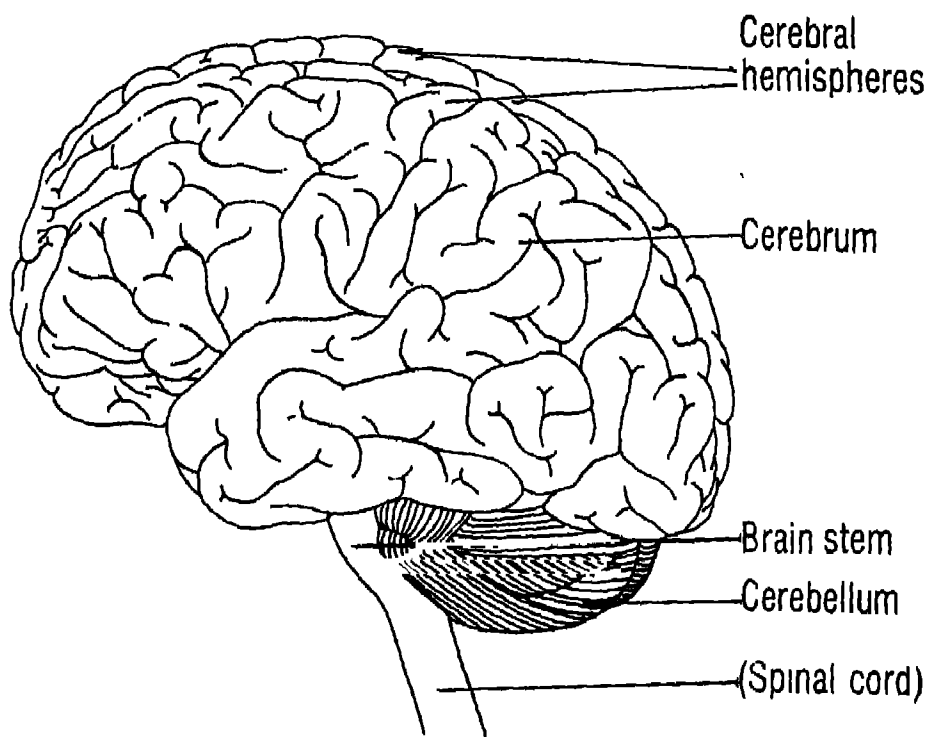


Fig. 38.1 External features of human brain (diagrammatic)

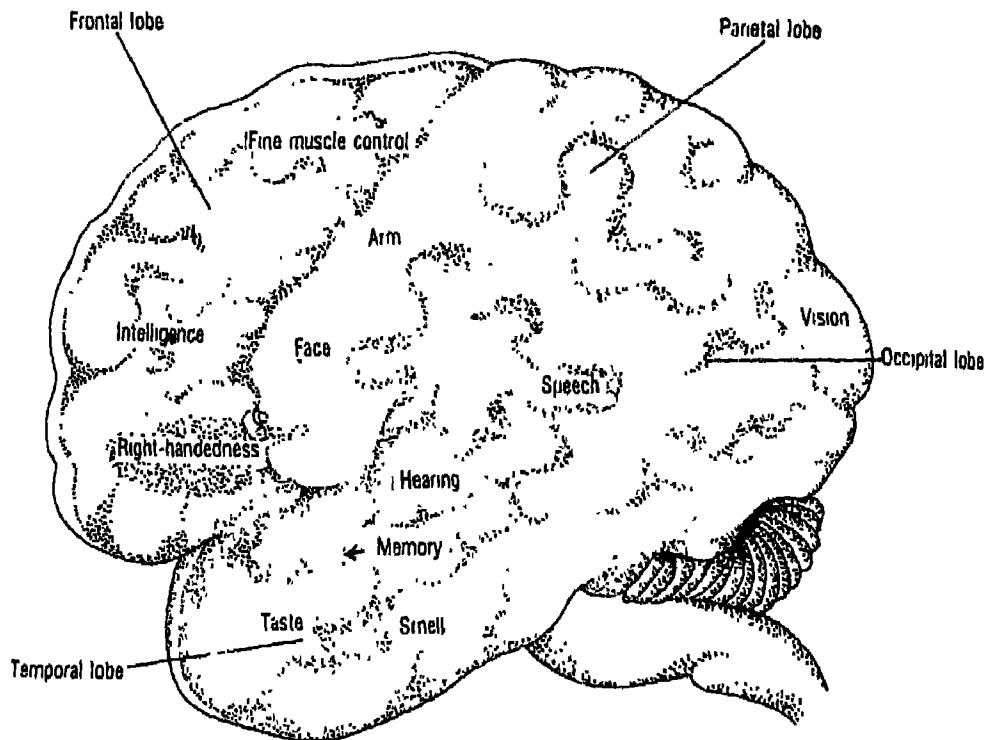
autonomic nervous system. The **VISUAL AREA** in the occipital lobe is the centre for visual sensation. The **AUDITORY AREA** in the occipital lobe is the centre for hearing. **ASSOCIATION AREAS** in the frontal lobe are responsible for association between various sensations and movements. Memory, intelligence and judgement depend on the coordinated and integrated activities of the neurons of different cortical centres.

**HYPOTHALAMUS** consists of number of scattered masses of the grey matter in the white matter at the base of the brain. It contains higher nerve centres for temperature regulation, hunger, thirst and emotional reactions. It secretes neurohormones which control the secre-

tions of anterior pituitary hormones. It synthesises the posterior pituitary hormones and control their release into the blood.

The **MIDBRAIN** contains many groups of nerve cells (nuclei) scattered in the white matter. Some of these nuclei are involved in controlling the muscles tone and modify some motor activities initiated by the cortex.

The hindbrain consists of a cerebellum located dorsally and the brain-stem ventrally. The **CEREBELLUM** like the cerebrum, has on its surface the cerebellar cortex consisting of the grey matter and in its deeper central part, the medulla



**Fig. 38.2** Cerebral cortex : Highest centres of many sensations and activities are located in this region of human brain.

made of the white matter; there are also cerebellar nuclei made of the grey matter, scattered in the white matter. The cerebellum, contains centres for the maintenance of posture and equilibrium of the body and for the muscle tone. Cerebellum also modulates and moderates the voluntary movements initiated by the cerebral cortex.

The **BRAIN-STEM** consists of pons varoli and medulla oblongata, the latter continuing into the spinal cord. The brain-stem contains centres for controlling many

vegetative activities, e.g. respiratory centres, vasomotor centres, salivary centre, etc. It also carries nerve tracts between the spinal cord and the higher brain centres.

The nerves arising from different parts of the brain are called CRANIAL NERVES. They will be described in connection with the peripheral nerves.

### *Spinal Cord*

The spinal cord is a cylindrical cord-like structure. It is situated in the bony canal

formed by the serial arrangement of vertebrae. The spinal cord extends downwards from the brain-stem. The grey matter forms a column running along the central part of the spinal cord; the central spinal canal, containing the cerebrospinal fluid, runs along the central part of the grey matter. The white matter forms an outer column surrounding the grey matter at its centre. From the lateral sides of the spinal cord, SPINAL NERVES emerge and go to supply peripheral tissues. They will be described in connection with the peripheral nerves.

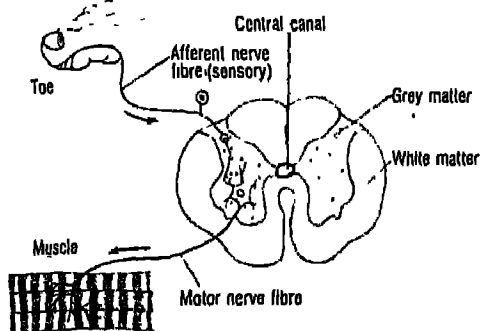


Fig. 38.3 Transverse section of the spinal cord of man showing main regions

In a cross-section of the spinal cord, its grey matter appears to be penetrating into the white matter in the form of horns (Fig.38.3). So, different areas of the grey matter are known as the dorsal, lateral and ventral horns according as they are located in the dorsal, lateral or ventral regions of the grey matter.

Bundles of nerve fibres ascend or descend along the white matter of the spinal cord. Such a bundle of fibres, originating and terminating at similar sites, is

called NERVE TRACT. The ASCENDING TRACTS conduct nerve impulses from the spinal cord to the brain; impulses are brought from the peripheral tissues by the in-coming spinal nerve fibres and are then conveyed to the brain through these tracts to produce sensations. The DESCENDING TRACTS conduct impulses from the brain to different levels of the spinal cord; impulses from their fibres are transmitted to ventral and lateral horn cells; axons of those cells conduct those impulses through the spinal nerves to muscles and glands.

### Peripheral Nervous System (PNS)

The peripheral nervous system includes the nerves running outside the central nervous system. Each nerve is composed of many nerve fibres enclosed by a connective tissue sheath. A nerve fibre is a long axon or dendrite of a neuron. The nerve fibres are classified as myelinated and non-myelinated fibres according to the presence and absence of myelin sheath around them.

The neurons and nerve fibres may also be classified depending on the direction of propagation of nerve impulses along them. Many neurons and nerve fibres conduct nerve impulses from the central nervous system to the peripheral organs and tissues. They are called EFFERENT NEURONS and EFFERENT NERVE FIBRES, respectively. Many other neurons and nerve fibres conduct impulses from the peripheral tissues and organs towards the central nervous system. They are known respectively as AFFERENT NEURONS and AFFERENT NERVE FIBRES.

The neurons and nerve fibres may again belong functionally to two classes. Some of them conduct nerve impulses to the muscles and glands to stimulate or

inhibit their activities. Many of these nerve fibres cause movements of muscles. So, such neurons and nerve fibres are known as MOTOR NEURONS and MOTOR NERVE FIBRES, respectively. The motor nerve fibres are the axons of motor neurons. The nerve fibres which reach nerve impulses to the eye muscles to control their movements, are motor fibres; so also are the fibres carrying impulses to the salivary glands and controlling their secretion. All motor neurons are efferent neurons because they conduct impulses from the CN system to the peripheral tissues, viz. muscles and glands. Other neurons and nerve fibres conduct nerve impulses from the peripheral tissues to the central nervous system to evoke sensations like touch, pain, heat, cold, taste, vision and hearing. They are respectively called SENSORY NEURONS and SENSORY NERVE FIBRES. They are all afferent in nature because they carry impulses from the peripheral tissues to the central nervous system. Sensory nerve fibres, conducting impulses from the skin, evoke touch, temperature or pain sensations; those conducting impulses from the retina give visual sensation.

Each nerve carries many nerve fibres. If it contains only sensory fibres, it is called a SENSORY NERVE. A sensory nerve conducts nerve impulses from peripheral tissues to the CN system to produce sensations. If a nerve contains only motor fibres, it is called a MOTOR NERVE. Its sole role is to conduct nerve impulses from the CN system to some muscle or gland to control their activities.

But some nerves carry simultaneously both sensory and motor nerve fibres. They are called MIXED NERVES and serve both sensory and motor functions. All nerves arising from the spinal cord are mixed

nerves.

### *Spinal Nerves*

Two spinal nerves arise from each segment of the spinal cord. There are 31 pairs of spinal nerves in man. Each spinal nerve is a mixed nerve, containing both sensory and motor nerve fibres and running between the spinal cord and the peripheral tissues. Near the spinal cord, the motor and sensory fibres of each nerve separate from each other to form two roots of the nerve. These two roots connect the spinal nerve to the spinal cord, one ventrally (or anteriorly) and the other dorsally (or posteriorly). The VENTRAL SPINAL NERVE ROOT contains only motor or efferent nerve fibres; these are axons of the nerve cells located in the ventral and lateral horns of the spinal cord. The ventral root fibres emerge from the spinal cord in the ventral root and, subsequently, run through the mixed spinal nerve to the muscles and glands in the peripheral tissues. Many of the ventral root fibres go to skeletal muscle fibres directly, many others leave the spinal nerve, go to some autonomic ganglia and end in them. The DORSAL SPINAL NERVE ROOT carries only sensory or afferent nerve fibres. At the middle of each dorsal root, there is a swelling called DORSAL ROOT GANGLION which houses the cell bodies of the sensory fibres of that dorsal root. The dendrites of these nerve cells pass through the mixed spinal nerve, conducting impulses from the peripheral tissues; they separate from the spinal nerve to enter its dorsal root and reach their cell bodies in the dorsal root ganglion; the axons of the dorsal root ganglion cells enter the spinal cord through the proximal segment of the dorsal root. The dorsal root fibres bring impulses from the peripheral tissues, giving rise to sensa-



tions like touch, temperature and pain, or to involuntary spontaneous activities, called reflexes.

### Cranial Nerves

The nerves arising from different parts of the brain are called cranial nerves. Man possesses twelve pairs of cranial nerves. Table 38.1 gives the names, natures, distributions and major functions of these

cranial nerves.

### Nerve Terminations

In the course of a nerve pathway, nerve fibres act in the form of relays. Each fibre terminates on some other nerve fibres of the pathway; at each such termination, nerve impulses have to be transmitted from the preceding fibre to the next fibre or fibres. In these cases, the axon of each neuron ends on the dendrite or the cell

Table 38.1  
CRANIAL NERVES

No.	Name	Fibres	Organs Innervated	Functions
1st	Olfactory	Sensory	Olfactory mucosa in nose	Smell
2nd	Optic	Sensory	<u>Retina of eye</u>	Vision
3rd	<del>Oculomotor</del>	Motor	Eyeball muscles, ciliary muscles, tear glands	<del>Eyeball</del> movements
4th	<del>Trochlear</del>	Motor	Eyeball muscle	<del>Eyeball</del> movement
5th	Trigeminal	Mixed	Skin, oral mucosa, muscles of head, face, mouth	Cutaneous sensation, muscle movements
6th	<del>Abducens</del>	Motor	Eyeball muscle	<del>Eyeball</del> movement
7th	Facial	Mixed	Taste buds, salivary glands, facial and neck muscles	Taste salivation, muscle movements, tear secretion
8th	Auditory	Sensory	Internal ear	Hearing, equilibrium sense
9th	Glossopharyngeal	Mixed	Pharynx, tongue, salivary glands	Taste, salivation, swallowing
10th	Vagus	Mixed	Pharynx, respiratory tract, heart, pancreas, alimentary canal, blood vessels	Gastric and pancreatic secretion, cardiac slowing, gastrointestinal movements, respiratory reflexes, vasomotor reflexes, visceral reflexes
11th	Spinal accessory	Motor	Neck and shoulder muscles, thoracic and abdominal viscera	Muscle movements, visceral reflexes
12th	Hypoglossal	Motor	Tongue muscles	Tongue movements

body of the next neuron. Such a junction between the terminations of two neurons is called a **SYNAPSE** and possesses specialised structure and properties. The nerve impulse is relayed across these synapses between successive neurons in a nerve pathway.

In the peripheral tissues the axon of a motor neuron terminates on either a muscle fibres or a gland cell. When it terminates on a muscle fibre, a specialised structure called the **MOTOR END-PLATE**, occurs at the neuromuscular junction (Fig. 38.4). Nerve impulses are transmitted across that junction from the axon terminal to the muscle fibre. The dendrite of a sensory neuron, on the contrary, terminates in the peripheral tissue on a structure specialised for receiving information about specific changes near it. This structure at the sensory nerve terminal is called a **RECEPTOR**.

### Receptors

An important function of the nerve fibres is to acquaint the animal with the changes inside the body and in the external environment. There are structures at the ends of the sensory nerve fibres for collecting information for this purpose. These structures are called **RECEPTORS**. Some receptors are specialised cells near the terminations of nerve fibres, e.g. rod and cone cells in the retina. Some other receptors are specially modified terminals of the nerve fibre itself, e.g. Pacinian corpuscles in the skin. But even nerve terminals showing no apparent specialised form or structure may serve as receptors in many cases; they are called **FREE NERVE ENDINGS** and are plentiful in the skin.

Each type of receptor is sensitive to only a specific type of stimulus or change. There are different receptors for touch,

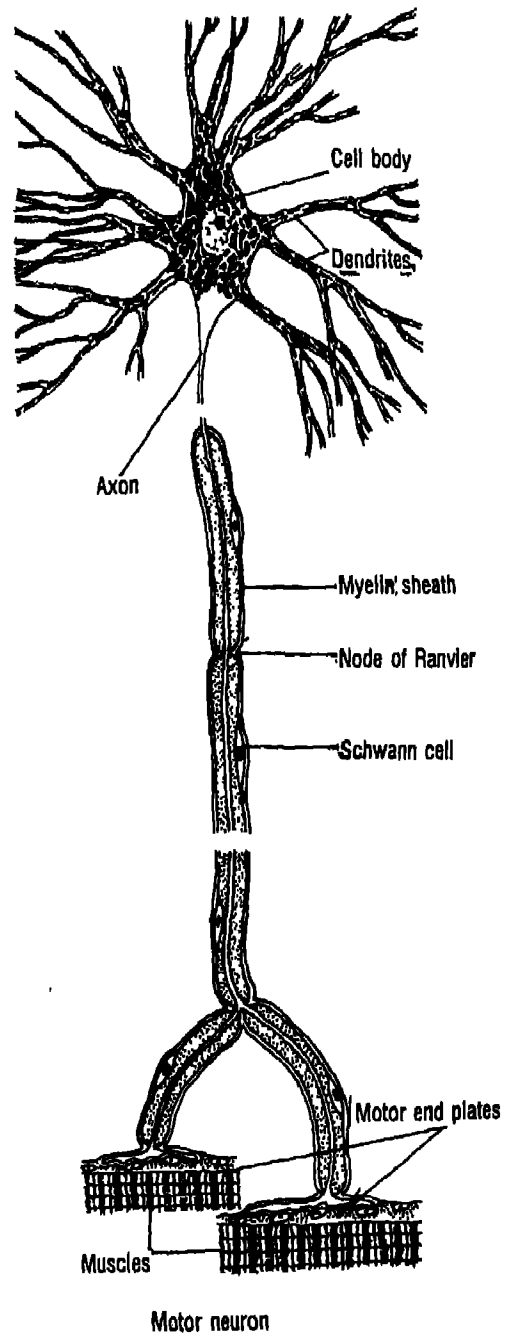


Fig. 38.4 Motor end-plates at neuromuscular junctions

As the chemicals stored in the synaptic vesicles help to transmit nerve impulses across the synapses, they are called **NEUROTRANSMITTERS**. A neuron is called **ADRENERGIC** or **CHOLINERGIC** according as it releases noradrenaline or acetylcholine as neurotransmitter at its axon terminals.

Nerve impulses are always transmitted across a synapse from the axon terminals of one neuron to the dendrite/cell body of the next neuron but never in the reverse direction. Since the neurotransmitter is present only in the axon terminals and not in the dendrite or cell body, it cannot be released from the dendrite or cell body even if the impulse reaches there. So, the impulse can never be transmitted from the dendrite or cell body of the next neuron to the axon of the preceding neuron across the synapse. This explains the one-way conduction. You may compare this to the relay race where the baton has to be transferred always from the first runner to the second because the latter carries the baton.

Just as a change of baton slows the relay run temporarily, there is delay in the transmission of the nerve impulses at each synapse. This interval, called the **SYNAPTIC DELAY** results from the time taken in releasing the neurotransmitter and in stimulating the next neuron by it.

The axon of a neuron may form synapses with several neurons; so, the nerve impulse from a neuron may diverge to several neurons at the synapse. Again, the axons of several neurons may synapse with a single neuron; this causes the impulses from all those axons to converge to a single neuron at the synapse.

On repeated transmission of nerve impulses through a synapse, there occurs a temporary suspension of impulse transmission at the synapse. This is called **SYNAPTIC FATIGUE**. It results from an exhaustion of the neurotransmitter in the synaptic vesicles of the axon terminal. After some time, the neurotransmitter accumulates again in the synaptic vesicles and the synapse regains its ability to transmit impulses.

pressure, temperature, chemical substances, stretch, light, sound, osmoconcentration and painful stimuli. The basic function of a receptor is to receive a particular stimulus and convert it to the form of electrical potential changes which then run along the associated nerve fibre as nerve impulses.

### **Synapse**

Nerve fibres carry nerve impulses in a relay. A synapse is the junction between two neurons, across which the impulse has to pass from one neuron to the next. It may be compared to the place where a

transfer of baton takes place between two runners in a relay race.

Synapses are formed between the axon terminals of one neuron and the dendrites, the cell body or even sometimes the axon of one or more neurons. There is no actual continuity between neurons at the synapse. The axon of a neuron divides near its termination into many branches, each branch losing its myelin sheath before termination. These axon terminals of a neuron then end in expanded foot-like forms on the dendrites or the cell body of another neuron; there is a narrow fluid-filled space, called **SYNAPTIC CLEFT**, sepa-

rating the membranes of the two neurons at the synapse. The axon terminal contains many membrane-bound vesicles, called **SYNAPTIC VESICLE**, in its cytoplasm. Within these vesicles, chemical substances, such as adrenaline and acetylcholine remain stored. When a nerve impulse passes the axon terminal, its synaptic vesicles release their stored chemicals to the synaptic cleft. These diffuse through the cleft to reach the membrane of the next neuron, and stimulating the latter. This causes the nerve impulse to be transmitted along the next neuron.

#### *Motor End-Plate*

You may recall that efferent or motor nerve fibres supply muscle fibres. The axon of the motor neuron divides into branches as it approaches the muscle fibres. Each branch loses its myelin sheath near its termination and ends in an expanded foot-like form which is applied closely to a muscle fibre (Fig. 38.4). Like synapse, here also there is no actual continuity between the neuron and the muscle fibre—the membranes of the two are separated from each other by a very narrow cleft-like fluid-filled space. Where the axon terminal is applied to the muscle fibre, the latter forms a specialised structure, called the **MOTOR END-PLATE**.

#### **Nerve Impulse**

In the resting nerve fibre, the cytoplasm just beneath its membrane is electronegative relative to the layer of extracellular fluid (ECF) just outside the membrane. If the two sides of the membrane are connected to a galvanometer, the inner side is seen to possess a negative potential of about  $-80\text{mV}$  relative to the outer side. This is called the **RESTING MEMBRANE POTENTIAL**. This results from two factors. On the one hand, the resting membrane

has only a poor permeability for  $\text{Na}^+$  although it has a higher permeability for  $\text{K}^+$ . On the other hand, the membrane carries a sodium pump; this actively carries three  $\text{Na}^+$  ions from the cell to the exterior and in exchange transfers two  $\text{K}^+$  ions from the ECF to the cell interior. These two factors, coupled together, result in a higher concentration of cations just outside the membrane compared to the concentration of cations just inside it. This state of the resting membrane is called POLARISED STATE and makes its inner side electronegative to its outer side.

A minimum strength of stimulus, called **THRESHOLD STIMULUS**, must be applied to the nerve fibre to stimulate it effectively. When the nerve fibre is effectively stimulated, its resting membrane potential undergoes a change—the inner side of the membrane now becomes electropositive to its outside. This potential change, called **ACTION POTENTIAL**, is propagated along the membrane of the nerve fibre as the nerve impulse. How does this action potential originate? Stimulation of the fibre immediately enhances manifold its membrane permeability to  $\text{Na}^+$ ; so,  $\text{Na}^+$  ions diffuse across the membrane from the ECF where their concentration is higher, to the interior of the fibre where the concentration is much lower. But the membrane permeability to  $\text{K}^+$  starts rising somewhat later only, so there is no simultaneous rise in the outward diffusion of  $\text{K}^+$  from the cell interior having a higher  $\text{K}^+$  concentration to the exterior with a lower  $\text{K}^+$  concentration. These effects lower the overall cation concentration outside and enhance that inside the membrane. The membrane is thus DEPOLARISED, with its interior becoming electropositive to the exterior.

How is the nerve impulse conducted

You can record the action potential by introducing a microelectrode inside the fibre, placing another electrode on the body wall, and connecting them to a recording instrument like the cathode ray oscilloscope. The membrane potential first rises sharply from about  $-80\text{mV}$  to about  $+60\text{mV}$  and almost immediately declines sharply to about  $+20\text{mV}$ ; these changes produce a spike-like record called the **SPIKE POTENTIAL**. The spike is followed first by a slower decline in the potential (**NEGATIVE AFTER-POTENTIAL**) and then by a potential more negative than the resting potential (**POSITIVE AFTER-POTENTIAL**). The potential then gradually returns to the resting value. These changes travel along the nerve fibre with the flow of the impulse.

along the nerve fibre? At the point of stimulation, the membrane of the fibre is depolarised with its outer and inner sides turning respectively electronegative and electropositive. Consequently, cations diffuse through the cytoplasm from the electropositive inner side of the depolarised part of the membrane to the electronegative region beneath the next inactive and polarised membrane; simultaneously, cations diffuse through the extracellular fluid from outside the polarised part to the electronegative area outside the depolarised membrane. This flow of ions depolarised the next inactive part of the membrane, producing the action potential there. Repetition of this process makes the action potential flow onwards as the depolarisation proceeds along the membrane.

In non-myelinated fibres, these ionic changes are repeated over the membrane all along the length of the fibre. So, the action potential flows all along the membrane over the entire length of the fibre. But in myelinated fibres, these ionic changes and the consequent depolarisation can take place only at the nodes of Ranvier free from myelin sheath, because the myelin sheath between the nodes insulates the fibre and prevents its depolarisation. So, the action potential in effect jumps from one node to the next. This is called SALTATORY CONDUCTION of nerve impulses. Because of this, nerve impulses do not have to run all along the myelinated nerve fibre. This is why nerve impulses are conducted far more rapidly in myelinated fibres than in non-myelinated ones.

The velocity of nerve impulses depends not only on myelination but also on the fibre diameter. The impulse travels slower in a thinner fibre than in a thicker one. Invertebrates like squids possess non-myelinated fibres only, so they must possess very thick nerve fibres for conducting impulses rapidly to distant parts like the long arms of squids. Giant squids, therefore, have very thick nerve fibres. But with the evolution of myelination, impulse velocity has increased manifold even in the thin fibres of vertebrates. This removes the necessity of having inconveniently thick fibres in an animal with long limbs.

#### *Reflex*

Spontaneous involuntary activities, evoked by the stimulation of receptors, are called **REFLEXES**. You may define a reflex as a spontaneous, involuntary, nerve-mediated activity produced at the unconscious level by stimulating specific receptors.

Each reflex is produced by the flow of nerve impulses along a specific nerve pathway called REFLEX ARC (Fig. 38.5). The reflex arc comprises some specific RECEPTORS, AFFERENT NEURONS from them to the CN system, EFFERENT NEURONS from the latter to specific muscle fibres or gland cells, and a varying number of CONNECTOR or INTERMEDIATE NEURONS conducting impulses from the afferent to the efferent neurons. A specific stimulus must be applied on a specific group of receptors to elicit the reflex. Stimulation of the receptors initiates a nerve impulse along the afferent neuron connected to them. The nerve impulse flows along the afferent, connector and efferent neurons to reach a muscle or gland, called an effector for that reflex. This produces either a movement of the muscle or the secretion of the gland as the effect of the reflex.

Impulses can flow only in a single direction in a reflex arc, viz. afferent → connector → efferent, because each synapse in a reflex arc allows impulses to cross it in a single direction. So, a reflex response can never be elicited in the receptors by stimulating the effector or the efferent neuron.

Repeated elicitation of a reflex may suspend the reflex response for some time, because synapses of the reflex arc suffer from fatigue.

**Unconditioned and Conditioned Reflexes:** Some reflexes can be evoked even immediately after birth and need no previous encounter with the stimulus exciting it. Taste of food causes salivation even in a new-born baby, or even though the baby is tasting that food for the first time. The pupil constricts even if the eye is illuminated with bright light just at birth. Such reflexes are called UNCONDITIONED OR INBORN REFLEXES. The stimulus for such a reflex is an unconditioned stimulus.

If an animal sees or smells some food hitherto unknown to it, for the first time, it does not salivate. But if it sees and smells the food every time before tasting it, after several trials it starts salivating reflexly. The foreign or indifferent stimulus, viz. the sight or smell of food, now becomes a stimulus for eliciting the reflex because repeated associations between the indifferent stimulus and the original unconditioned stimulus (i.e. taste of food) have conditioned the nervous system to expect the unconditioned stimulus to fol-

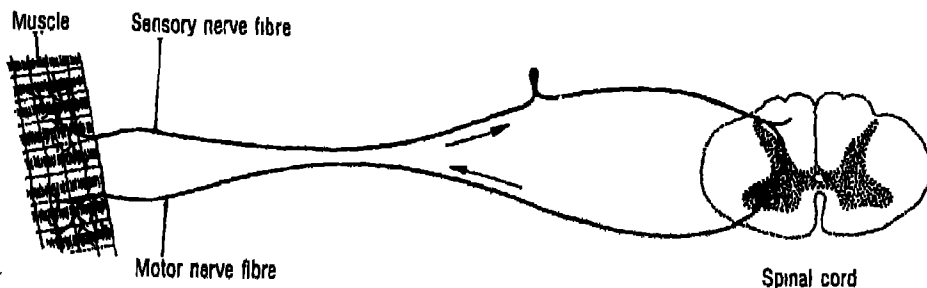


Fig.38.5 Reflex arc—a minimum nerve circuit between stimulus and response

low shortly. Such a reflex, acquired after birth by applying an indifferent stimulus before or along with the stimulus for an in-born reflex, is called a CONDITIONED OR ACQUIRED REFLEX. The stimulus which has now acquired the capacity to evoke the reflex, is called CONDITIONED STIMULUS. The sight or smell of food is a conditioned stimulus for salivation.

V.P. Pavlov, the famous Russian neurophysiologist, discovered and experimentally established conditioned reflexes in animals. He sounded a gong every time before he gave some meat to his dog to eat. After several repetitions of this act, the dog was found to salivate with the sounding of the gong even when the gong was not followed by food. The sound of gong became a conditioned stimulus for the salivary reflex of the dog.

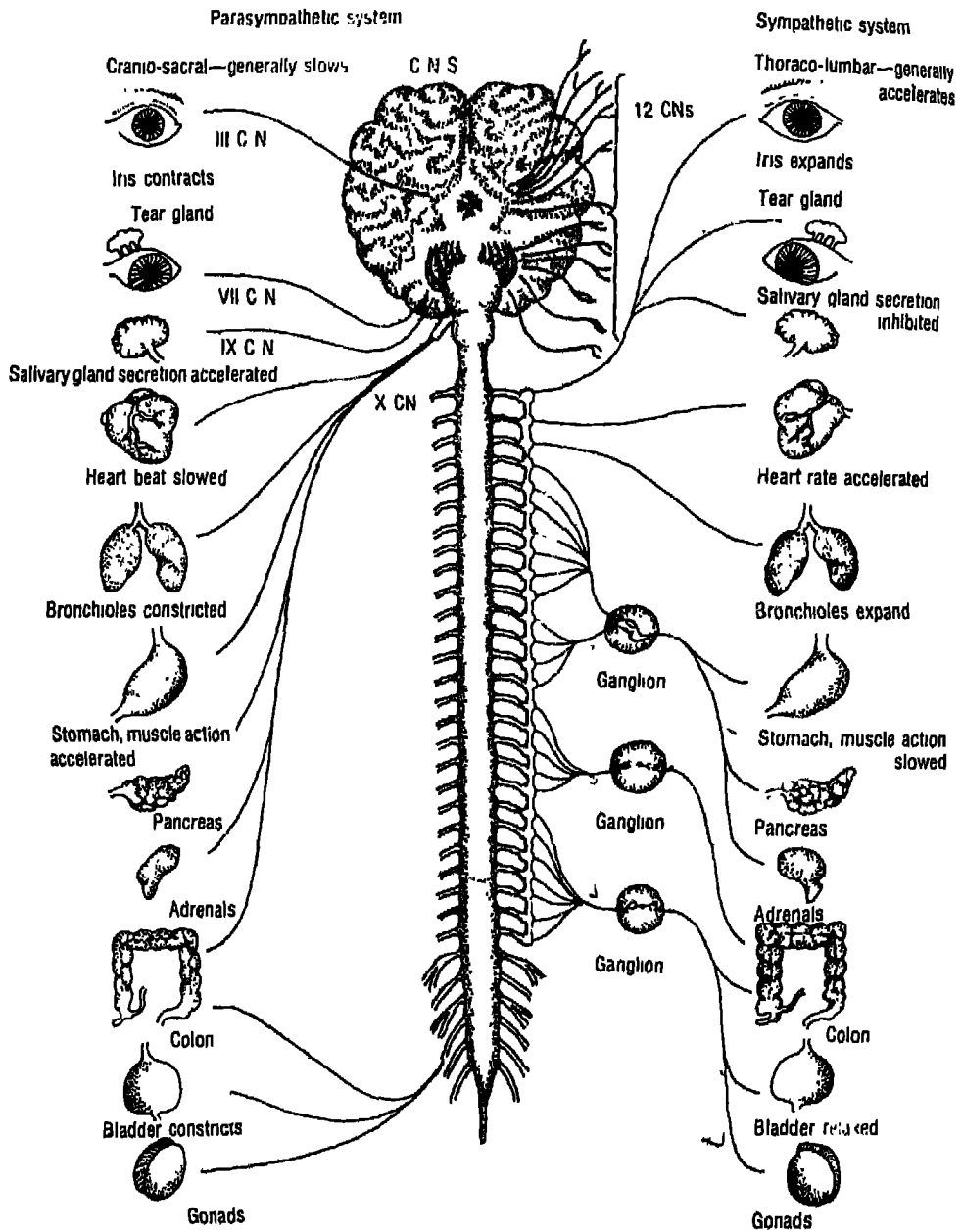
### The Autonomic Nervous System

Movements of skeletal muscles are regulated by nerve fibres directly from the CN system. But the activities of the visceral organs are coordinated through the regulation of their smooth muscles and glands by the nerve fibres of the autonomic or visceral nervous system. Some motor nerve fibres, emerging from the CN system pass to AUTONOMIC GANGLIA which are swollen, bulbous structures containing the cell bodies of many neurons. The nerve fibres, thus entering the autonomic ganglia, are called PREGANGLIONIC FIBRES; they terminate by synapsing with the nerve cells in the autonomic ganglia. The axons of these ganglion cells emerge from the ganglia as POSTGANGLIONIC FIBRES and supply smooth muscles and

glands. These preganglionic and postganglionic fibres and the autonomic ganglia together constitute the autonomic nervous system (AN system). Postganglionic autonomic fibres conduct impulses to smooth muscles and glands only when the CN system sends impulses through the preganglionic fibres. Moreover, the AN system is ultimately regulated by higher nerve centres of the brain. So, the AN system is far from possessing full autonomy or complete independence from the CN system although the word 'autonomic' implies its autonomy.

The autonomic nervous system is divided anatomically as well as functionally into two divisions—the sympathetic and the parasympathetic nervous systems. Each possesses its own set of pre-and post ganglionic fibres and ganglia. But whereas the sympathetic nervous system, as you will presently read, is consolidated into a visibly distinct anatomical entity, the parasympathetic system does not possess such visibly consolidated form. The preganglionic fibres of the sympathetic system emerge from the thoracic and lumbar spinal segments; so, these fibres form the THORACICO-LUMBAR OUTFLOW. In contrast, preganglionic parasympathetic fibres emerge from the brain and the sacral spinal segments; so, they constitute the CRANIO-SACRAL OUTFLOW.

The SYMPATHETIC NERVOUS SYSTEM (Fig. 38.6) possesses two lateral chains of ganglia, one on each side of the spinal cord. Each chain is made up of many lateral ganglia, connected serially by nerve fibres running between them. The preganglionic sympathetic fibres are axons of lateral horn cells of thoracic and lumbar spinal segments. Each preganglionic fibre leaves the spinal cord through the ventral spinal nerve root, emerges from the spinal



**Fig. 38.6** Central and Autonomic Nervous Systems of Man  
(CNS = Central nervous system; CN = Cranial nerve).



nerve and, after a short course, enters a ganglion of the lateral sympathetic chain. The fibre branches inside the latter and its branches end in several ganglia, synapsing with their ganglion cells. The postganglionic fibres are the axons of those cells and are much longer than the preganglionic ones. Postganglionic fibres emerge from the ganglia, course back to re-enter the spinal nerve and run through the latter to the tissues. Some preganglionic fibres, however, pass through the lateral ganglia without terminating there; instead, they emerge from the lateral chain, pass to some isolated ganglia nearer to the tissues and away from the chain, and end in those ganglia. Such ganglia are called COLLATERAL GANGLIA; postganglionic fibres from them supply peripheral tissues.

The PARASYMPATHETIC NERVOUS SYSTEM (Fig. 38.6) consists of parasympathetic ganglia situated very close to the peripheral tissues. They are not interlinked with each other to form any chain of ganglia. Preganglionic parasympathetic fibres are axons either of lateral horn cells of sacral spinal segments or of nerve cells situated in the midbrain and the brain-stem. They emerge from the CN system, run a long course towards the peripheral tissues and terminate in individual ganglia near those tissues. Postganglionic fibres are the axons of the ganglion cells. They terminate in smooth muscle fibres or glands after a short course. Unlike the sympathetic system, preganglionic parasympathetic fibres are much longer than the postganglionic ones, and each of them terminates in a single ganglion instead of giving branches to several ganglia.

Autonomic fibres innervate the smooth muscles on the walls of the blood vessels, gastrointestinal tract, respiratory tract, reproductive tract, urinary bladder, iris

muscles and ciliary muscles in the eyes. They also innervate glands such as gastrointestinal, salivary, pancreatic, tear and sweat glands. The sympathetic and parasympathetic autonomic nervous systems are often antagonistic in their actions. For example, sympathetic nerves enhance the force and the rate of heart beats, constrict most blood vessels, raise the arterial blood pressure, dilate the pupil, reduce gastrointestinal movements, and relax the urinary bladder. Parasympathetic nerves, on the contrary, decrease both the rate and the force of heart beats, dilate many blood vessels, lower the blood pressure, constrict the pupil, increase gastrointestinal movements, and contract the urinary bladder. A balance between the sympathetic and the parasympathetic actions helps to maintain constancy of the internal environment of the body. For example, a balance between the actions of sympathetic and parasympathetic nerves on the blood vascular system maintains the normal heart rate, cardiac output and arterial blood pressure.

Sympathetic nerves stimulate the adrenal glands to secrete adrenaline. Postganglionic sympathetic fibres are mostly ADRENERGIC, i.e. they release the neurotransmitter noradrenaline at their terminations. So, sympathetic nerves act with the adrenals as a well-integrated sympathetic-adrenal system having widespread effects. Moreover, each preganglionic sympathetic fibre, you may recall, transmits nerve impulses to many postganglionic fibres arising in several ganglia. So, sympathetic nerves simultaneously affect many organs and tissues to produce widespread and coordinated effects. This enables the (sympathetic-adrenal system to play important roles in combating emergencies).

In contrast, a preganglionic parasympathetic fibre synapses with postganglionic fibres in a single ganglion; its impulses are thus ultimately transmitted to only a specific organ or tissue. This localises each parasympathetic action to limited areas, mostly to a single organ or a close group of organs. The parasympathetic nervous system is more concerned in maintaining daily vegetative activities. For example, the parasympathetic fibres of the vagus nerve (the tenth cranial) stimulates gastric and pancreatic secretions and gastrointestinal movements to help digestion; parasympathetics of the pelvic nerve stimulate bladder contractions for voiding urine.

In contrast to most postganglionic sympathetics, postganglionic parasympathetic fibres are CHOLINERGIC—they liberate acetylcholine at their endings for the transmission of nerve impulses. Preganglionic fibres of both sympathetic and parasympathetic systems are cholinergic.

### Special Senses

Special senses include the senses for vision, hearing, smell and taste. Organs for special senses are the eyes, ears, nose and tongue.

#### Vision

The eyes are the sense organs for vision. They contain receptors called PHOTORECEPTORS, viz. rod and cone cells, which convert the energy of specific wavelengths of light into action potentials of nerve fibres.

The HUMAN EYES are located in the bony orbital cavities and are cushioned in fatty connective tissue. The wall of each eyeball is made up of three concentric layers (Fig. 38.7). An opaque, fibro-elastic capsule, called SCLERA, and a transparent layer, called CORNEA, form respectively,

the posterior five-sixths and the anterior one-sixth of the outer layer of the eyeball. Striated muscle fibres for eyeball movements are inserted into the sclera; nerve fibres of the 3rd, 4th and 6th cranial nerves control them to move the eyeball for looking at different directions. Light enters the eye through the transparent cornea; due to its curvature, the cornea roughly focuses a real inverted image of visual objects almost on the light-sensitive inner layer or retina. The middle layer consists of the choroid, the ciliary body and the iris. The CHOROID is a highly vascular pigmented layer separating the sclera from the inner layer of the eyeball. It is connected in front to a thick structure, called CILIARY BODY. The latter contains smooth muscle fibres constituting CILIARY MUSCLES and throws folds, called ciliary processes, into the eye chamber. Thread-like suspensory ligaments extend from the ciliary body and get attached to the equatorial edge of a biconvex transparent LENS. The latter is an elastic structure made mainly of non-nucleated, transparent and elongated cells. A pigmented, muscular, opaque diaphragm, called IRIS, extends from the ciliary body in front of the lens. It can be seen as a black screen through the cornea and has a small central aperture, called PUPIL. Light passing through the cornea enters through the PUPIL to fall on the lens behind it; the lens then focuses the light to form a sharp, well-defined, real, inverted image of the object on the retina. The iris has two sets of smooth muscles arranged circularly and radially around the pupil; the pupil is respectively constricted and dilated by their contractions to reduce and increase the amount of light falling on the lens. The inner layer of the posterior two-thirds of the eyeball consists of a light-sensitive

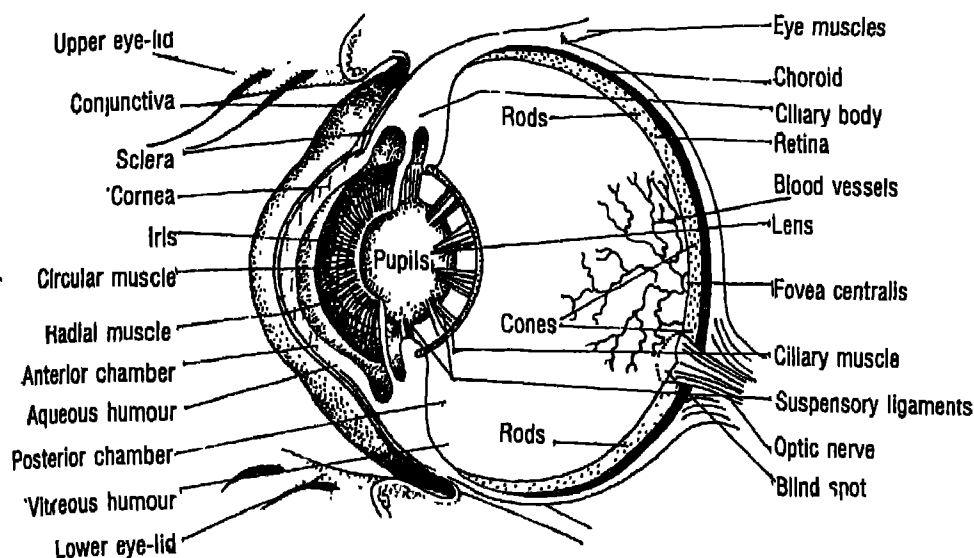


Fig. 38.7 Structure of human eye (diagrammatic)

layer, called **RETINA**. The retina is made up of many layers of cells and fibres. It contains two types of photoreceptors, viz. **ROD AND CONE CELLS**, and four types of neurons including bipolar nerve cells and ganglion cells (Fig. 38.8). Both rods and cones contain light-sensitive pigments formed from vitamin A. When light reaches these receptor cells, the light-sensitive pigments are broken up by specific wave lengths of light; this stimulates the receptor cells. Then, nerve impulses are carried from rods and cones by the bipolar nerve cells to the ganglion cells. The axons of the ganglion cells converge and leave the eyeball to form the **OPTIC NERVE**. They conduct nerve impulses from the eyeball to the brain. The spot at the back of the eye from where the optic nerve fibres leave is covered by a zone of retina free from rods and cones. So, this spot is devoid of the ability for vision and is

called the **BLIND SPOT**. Lateral to the blind spot, there is a depressed area of the retina, called **FOVEA**, which contains only cones and no rods. Ability for vision is highest in the fovea; when eyes are fixed on an object, its image is focused on the fovea and is consequently seen most accurately.

The cavity inside the eyeball is divided by the lens, ciliary body and suspensory ligaments into an anterior compartment and a posterior compartment. The anterior compartment is filled with an aqueous fluid, called **AQUEOUS HUMOR**. It supplies nutrients to the lens and the cornea having no blood supply; by its pressure, it maintains the shape of the cornea and supports the lens. The posterior compartment is filled with a transparent gelatinous material called **VITREOUS BODY**; the latter supports the lens and the retina.

The human eye is sensitive only to light

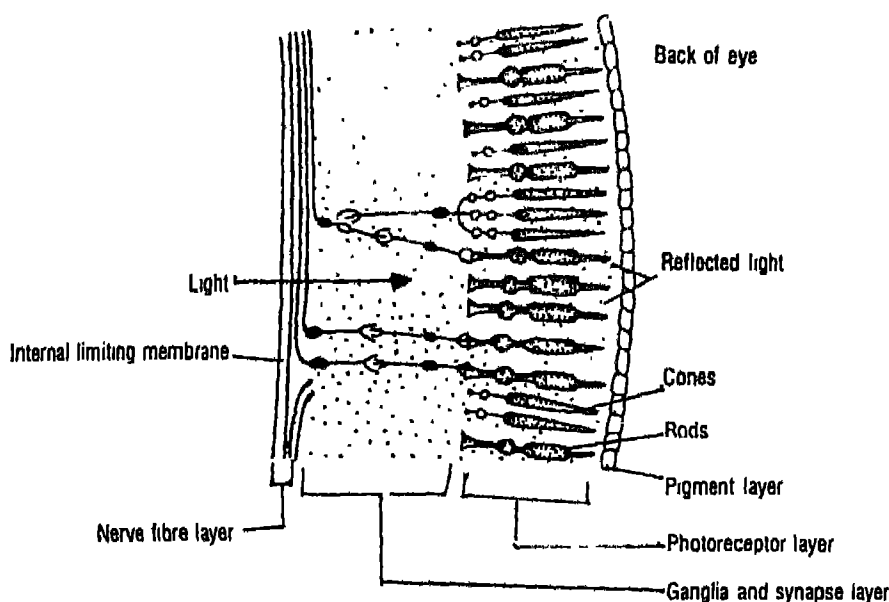


Fig. 38.8 Structure of retina in a sectional view (diagrammatic)

wavelengths ranging from 380 to 760 nanometres. RODS are sensitive even to dim light and consequently enable us to see in dim light and at night. They contain a purple-coloured photosensitive pigment, called RHODOPSIN, formed from vitamin A. Many nocturnal animals, like owls, have only rods or mainly rods as photoreceptors in their retina; this endows them with a high ability to see in the darkness. You may recall that the vitamin A deficiency causes night-blindness in man because rods cannot function if rhodopsin is not synthesised from vitamin A. Rods, however, cannot help in seeing colours. You must have noticed that a red flower looks black in the evening; this is because only rods function in such dim light and they possess very little sensitivity to red light.

CONES are sensitive to bright light only. So, they help us to see in day light or in a

room illuminated brightly with electric lamps. Animals, like sparrows, which are active only in day time, have only or mostly cones in their retina and possess poor night vision. Cones are also responsible for the perception of colours. Like rods, cones also contain violet-coloured photosensitive pigment such as iodopsin.

Specific light wavelengths cause photochemical changes in the cone pigment. This stimulates the cone from which a nerve impulse is transmitted through the optic nerve fibres to the brain.

Human beings, apes, monkeys, birds, lizards, turtles and some fishes possess colour vision. But most domestic mammals and sharks do not possess colour vision. The visible range of spectrum varies among animals—bees, for example, can see ultraviolet light, which is invisible to man.

For proper vision light rays from a visual object must be focused sharply and precisely on the retina. In the resting eye, the ciliary muscles remain relaxed, keeping the suspensory ligaments stoutly stretched; the stretch by the suspensory ligaments flattens the elastic lens to reduce its curvature. The lens in this resting eye focuses parallel rays from distant objects (more than 6m away) on the retina. But a reflex, called **ACCOMMODATION**, is needed to increase the power of the lens for focusing divergent rays from near objects on the retina. In this reflex, the parasympathetic fibres of the third cranial nerve cause contraction of the ciliary muscles; this slackens the suspensory ligaments and reduces their stretching action on the lens (Fig. 38.7). The lens consequently increases its curvature due to elasticity and its power is enhanced. It can now focus the divergent rays on the retina. In some animals, like fishes, accommodation for near objects is brought about by elongating the eyeball instead of increasing the lens curvature.

### Hearing

The ears are the sense organs for hearing. The ear consists of an external ear, a middle ear and an internal ear. It houses receptors for both hearing and body equilibrium. Sensory hair cells in the cochlea of the internal ear serve as **AUDITORY RECEPTORS** for hearing. They convert the energy of sound waves into action potentials of nerve fibres. The hair cells in other parts of the internal ear serve as receptors for postural changes, acceleration and change of orientation of the body in space. Thus,

the auditory part of the ear is restricted to the external ear, the middle ear and the cochlea of the internal ear; other structures of the internal ear are concerned with posture and equilibrium.

Eyes, capable of focusing the images of objects, are possessed only by vertebrates and some higher invertebrates like prawns, crabs and insects. The anatomy of the eye differs widely in these animals. For example, prawns, crabs and cockroaches possess **COMPOUND EYES**, each made up of many elongated tube-like units, called **OMMATIDIA**. Ommatidia are crowded over a spherical surface. Each focuses the light from a small area of the object so that a mosaic of a large number of images of the adjacent areas of the object are formed by numerous ommatidia. A fusion of these images may produce a composite blurred image of the object.

In man, the **EXTERNAL EAR** consists of an immovable cartilaginous ear-lobe or **PINNA**, and an external auditory canal leading inwards from it through cranial bones (Fig. 38.10). The pinna is somewhat funnel-shaped. It collects and directs sound waves into the external auditory canal. The pinna is much larger and movable in many mammals like cattle, dogs, cats and elephants; there it serves its purpose much better by being directed towards the source of sound like the radar antenna. The external auditory canal ends at a delicate membranous diaphragm, called **EARDRUM** or **TYMPANIC MEMBRANE**. The **MIDDLE EAR** is an air-filled chamber on the other side of the ear-drum and inside the cranial bone. Its cavity communicates with that of the pharynx

REFRACTIVE ERRORS of the eye are quite common in man. MYOPIA or short-sightedness results from either an abnormally long eyeball or an abnormally high curvature of the lens. It results in the focusing of parallel rays from distant objects in front of the retina instead of on the retina (Fig. 38.9). It is corrected by spectacles with biconcave lenses which diverge the parallel rays before their entry into the eye; this brings the rays to a sharp focus on the retina. HYPEROPIA or HYPERMETROPIA results from either an abnormally short eyeball or an abnormally low convexity of the lens. It results in the parallel rays from distant objects getting focused beyond the retina. It is corrected by using biconvex lenses which supplement the refractive power of the eye lens to focus the parallel rays on the retina. ASTIGMA-

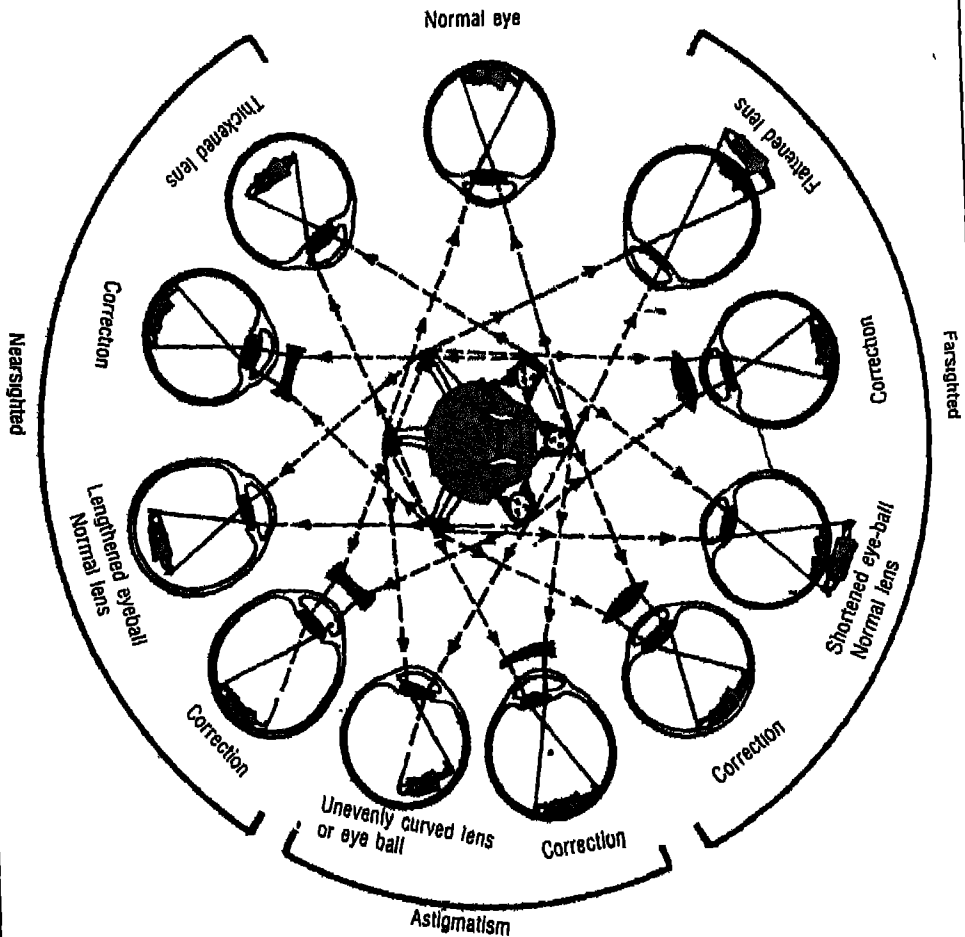


Fig.38.9 Some common defects of the eye and their corrections

TISM results from the difference in curvature between different meridians of the cornea. Light rays passing through different meridians of the cornea suffer different degrees of refraction and are consequently focused at different points, blurring the image. It can be corrected by using cylindrical lenses in specific meridians to make the refraction identical in all meridians. PRESBYOPIA results from a reduction in the elasticity of the lens with age, particularly above 40. It leads to a failure of accommodation for viewing near objects. It is corrected by using convex lenses for near vision.

CATARACT is an opacity of the lens. It is caused by the denaturation of lens proteins due to various causes. It results in the loss of vision and is corrected by the surgical removal of the opaque lens and the use of spectacles with convex lens. Diabetes may cause cataract even at an early age. Modern treatment of cataract comprises introduction of an artificial lens surgically into the eye.

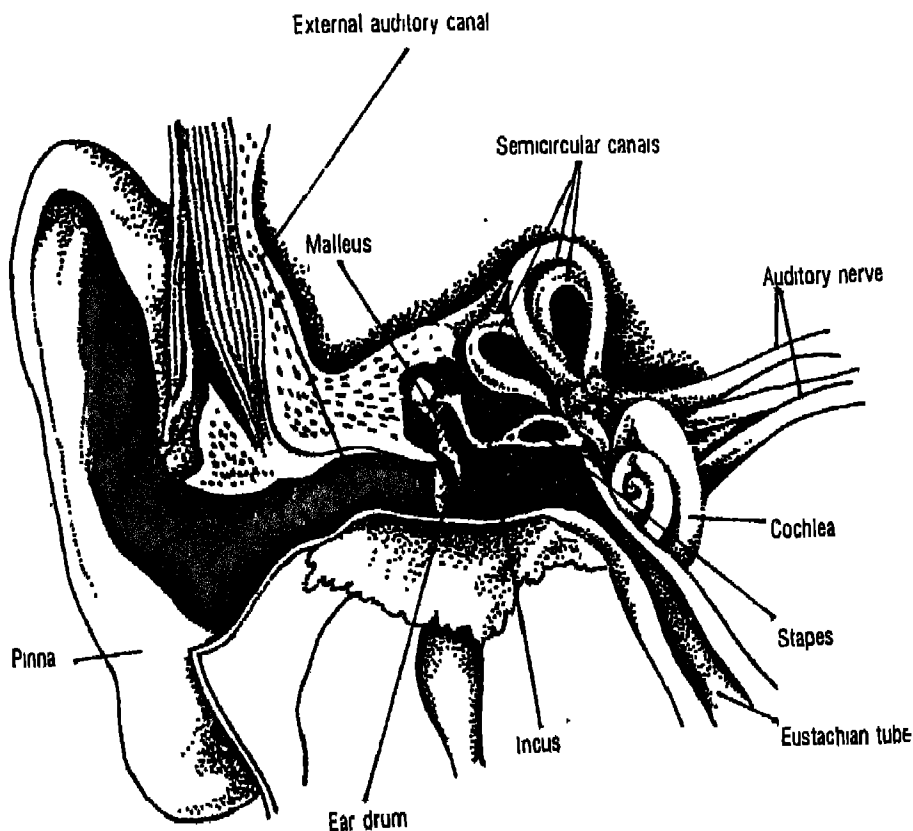


Fig. 38.10 Structure of human ear (sectional view)

through an air-filled tube, called EUSTACHIAN TUBE. The latter maintains the balance in air pressure between two sides of the eardrum and thus allows it to vibrate freely when sound waves impinge on it. There are three small bones, called AUDITORY OSSICLES, in the cavity of the middle ear. Of the ossicles, the hammer-like MALLEUS is attached, on one hand, to the eardrum and articulates, on the other hand, with the anvil-like INCUS; the latter articulates in turn, with the stirrup-like STAPES the foot plate of which is attached to the membrane over an oval window between the middle and the internal ears (Fig. 38.10). The auditory ossicles transmit the sound-induced vibrations of the eardrum to the fluid ENDOLYMPH filling the internal ear. The INTERNAL EAR is made up of a BONY LABYRINTH and a MEMBRANOUS LABYRINTH. The bony labyrinth consists of several bony cavities and canals filled with a fluid, called PERILYMPH. In this perilymph inside the bony labyrinth, the membranous labyrinth floats. The latter consists of several membranous canals and sacs, all filled with the endolymph. The bony labyrinth has three bony SEMI-CIRCULAR CANALS, an irregularly shaped bony cavity, called VESTIBULE and a conch shell-like coiled bony tube, called COCHLEA. The membranous labyrinth has three membranous semicircular canals, a coiled membranous tube inside the cochlea, and two sacs, called UTRICLE and SACCULE inside the vestibule. The membranous semicircular canals, utricle and saccule carry hair cells acting as receptors for acceleration, postural changes and change of orientation. The membranous cochlea, also called SCALA MEDIA, is filled with endolymph and has a spirally coiled BASILAR MEMBRANE forming one of its walls. Several rows of hair cells serving as auditory

receptors are located on the basilar membrane all along its coiled course to form the ORGAN OF CORTI. The endings of auditory nerve fibres are associated with these auditory hair cells.

The ear detects a sound, locates its direction, estimates its loudness and perceives its pitch (frequency). The human ear can hear sounds of pitches ranging from 16 to 20,000 cycles per second. But bats produce and hear ultrasonic sounds of pitches far above the human audibility limit, for navigation during flying. Sound waves reach the ear-drum through the external auditory canal and vibrates the eardrum. The vibrations of the latter are transmitted by the auditory ossicles to the oval window (fenestra vestibuli) and thence the endolymph inside the scala media. The resulting vibrations of the endolymph cause a specific segment of the basilar membrane to vibrate by resonance. This stimulates the hair cells overlying that segment. Nerve impulses are conducted by auditory nerve fibres from those hair cells to the brain and, ultimately, reach a specific area of the auditory cortex depending on the membrane segment affected. The pitch of the sound is perceived according to the area of the AUDITORY CORTEX receiving the nerve impulses. The loudness of the sound is perceived by the rate of nerve impulses reaching the auditory cortex.

### Smell

Smell or olfaction, like taste sensation to be described later, is evoked by specific chemical substances stimulating the receptors concerned. The nose may be called the sense organ for olfaction. Receptors for smell occur in a modified form of pseudostratified epithelium covering a part of the nasal mucosa (Fig. 38.11). This



epithelium is called **OLFACTORY EPITHELIUM**. It lines the surface of only a small area (about  $5\text{ cm}^2$ ) in the roof of the nasal cavity near the nasal septum in man. But it is far more extensive in animals like dogs, with an acute olfactory sense. The olfactory epithelium consists of three types of cells, viz. olfactory receptor cells, sustentacular or supporting cells and basal cells. The olfactory receptor cells function as **CHEMORECEPTORS** because they are stimulated by specific chemical substances.

If a person continuously inhales a substance evoking intense smell, the smell sensation progressively and rapidly weakens for that substance and ultimately disappears. This **OLFACTORY ADAPTATION** results from changes in both the olfactory receptor cells and the olfactory centres of the brain. You may be aware that when you apply a perfume on your body or dress you soon cease to smell it yourself but others approaching you can still perceive its aroma. Similarly, a disagreeable odour becomes more tolerable if you get it continuously for a long time.

All animals do not have their olfactory receptors located in the nose. Moths and butterflies, for example, possess olfactory chemoreceptors on their antennae. Sometimes, a male moth can smell a female several miles away and fly unerringly to meet her.

Many thousand types of odour are perceived by man. A far larger number of odours must be discernible to dogs and insects. You are aware that dogs can track people because they can distinguish between the odours of different persons. But how so many types of odour are discriminated from each other, is not properly

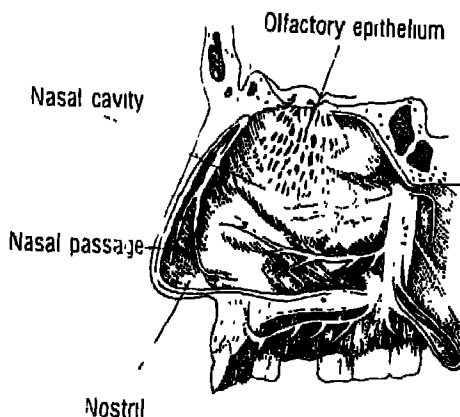


Fig. 38.11 Nose, the sense organ for olfaction (sectional view)

known yet.

### Taste

**TASTE BUDS** (Fig. 38.12) are the sense organs for taste sensation. They occur mainly in the mucous membrane over small projections (papillae) on the surface of the tongue. Some taste buds are also scattered in the mucous membrane of the pharynx, palate and epiglottis. The human tongue bears about 10,000 taste buds in its papillae. A papilla may contain a few to about hundred taste buds. Each taste bud is an oval barrel shaped structure opening on the tongue surface through a pore called the taste pore. The taste bud measures about 50 micrometres in size and contains about 60-70 spindle-shaped cells. Of the latter, **TASTE RECEPTOR CELLS (GUSTATORY CELLS)** number about 5-15; these cells look lighter and possess long hair-like

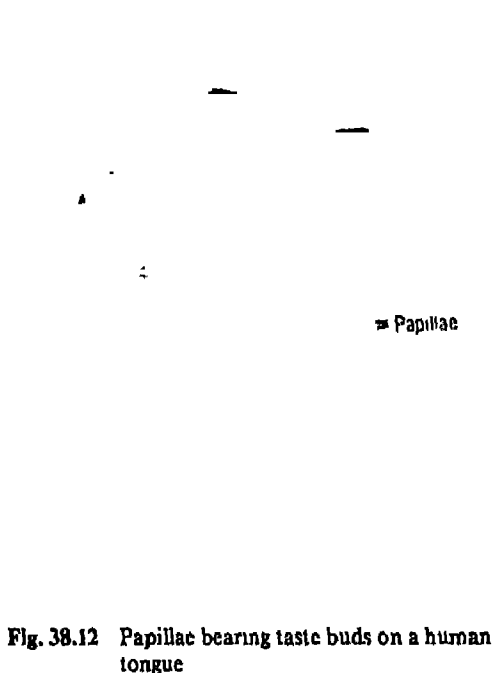


Fig. 38.12 Papillae bearing taste buds on a human tongue

microvilli projecting into the taste pore. Nerve fibres end around gustatory cells,

forming synapses with them. When the gustatory cells are stimulated, these fibres carry impulses for taste sensation to the brain. About 40 supporting cells occur between the gustatory cells in a taste bud.

**Gustatory cells** function as **CHEMORECEPTORS**—they are stimulated by specific chemical substances acting on them. Substances dissolved in the salivary water flow into the taste bud through the taste pore to reach the gustatory cells. When taste-evoking substances stimulate those cells, a nerve impulse originates and runs along the sensory fibres associated with gustatory cells. Nerve fibres, emerging from the taste buds pass to the brain stem through the facial, the glossopharyngeal and the vagus nerves. From the brain stem, the nerve impulses are relayed through other neurons to reach finally the **TASTE CENTRE** below the somesthetic area of the cerebral cortex. It perceives the taste sensation.

Human beings recognise four **BASIC MODALITIES OF TASTE**, viz. sweet, sour, salty and bitter. No structural difference is discernible between the taste buds in different areas of the tongue; still the taste buds in different areas seem to differ in their sensitivity to different basic tastes. Sweet, sour, salty and bitter tastes are principally perceived at the tip, along the lateral edges, on the upper surface of the front half, and on the back of the tongue, respectively (Fig. 38.13). Some taste buds are stimulated by a single specific modality of taste like sweet or sour; others are sensitive to two or more modalities. Sour taste is evoked by  $H^+$  ions produced by the ionisation of acids. Sweet taste is evoked mainly by organic substances of diverse natures such as sugars, dextrins, glycerol, chloroform, aspartame and saccharine. Saccharine and aspartame are widely used as artificial sweetening agents—a diabetic who cannot take sugar can use saccharine to sweeten his tea. Bitter taste is evoked by many organic substances like quinine, morphine, caffeine, nicotine and urea. It is also produced by the cations of many inorganic salts like magnesium salts. Salty taste results mainly from some cations like  $Na^+$  of inorganic salts and also by some organic substances. Taste and smell are closely related sensations. Loss of smell reduces the perception of taste also. You must have noticed how the taste of a food is much reduced when nasal passages are blocked in common cold preventing smell sensation.

Taste of chillies, black pepper and 'hot' sauces is not a true sensation. It is

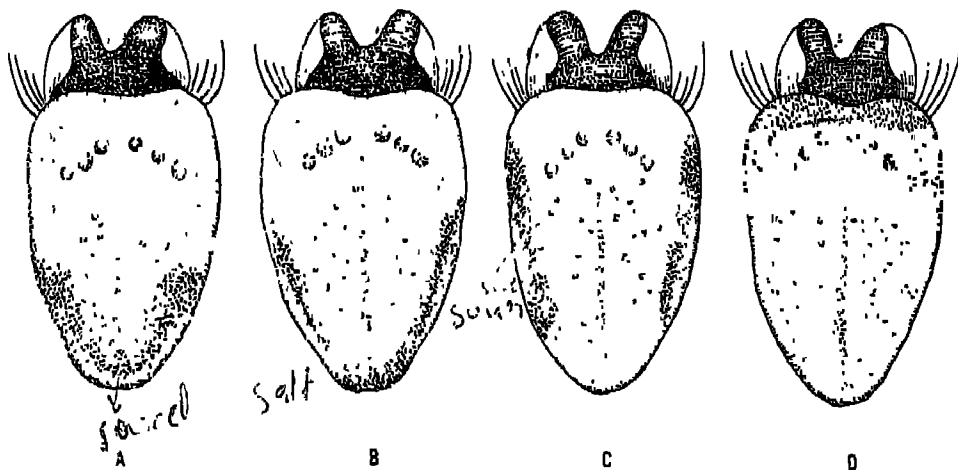


Fig. 38.13 Areas of human tongue perceive different tastes (dark coloured): A. Sweetness; B. and C. Saltiness and sourness; D. Bitterness

mainly a sensation of burning pain produced by the stimulation of pain receptors of the tongue by specific chemical substances in those foods.

Many insects such as honeybees, flies, butterflies and moths possess chemoreceptors for taste sensation on their feet. They start sucking a sugar solution as soon as it is applied to their feet.

Some mammals such as rhesus monkeys, pigs, cats and dogs possess some taste buds which send nerve impulses to the brain along the facial nerve when distilled water is applied on them. It seems, therefore, that water may stimulate those taste buds to evoke taste sensation in those animals. Man does not possess taste buds for tasting water.

Taste of food is of vital importance in the process of digestion, because taste stimulates reflexes causing secretions of saliva, gastric juice and pancreatic juice.

## SUMMARY

The nervous system receives information about external and internal changes, conducts such information between different parts of the body and coordinates the activities of different organs and tissues in the light of those changes. In mammals, the

nervous system consists of the central nervous system comprising the brain and the spinal cord, and the peripheral nerves coursing outside the central nervous system.

The central nervous system contains nerve centres for all sensations and activities. The brain and the spinal cord are covered by membranes, called meninges. The cavities of the cerebral ventricles inside the brain and the cavity between meninges contain the cerebrospinal fluid.

The brain consists of the forebrain, the midbrain and the hindbrain. The cerebrum of the forebrain consists of two cerebral hemispheres and shows many convolutions, called gyri. The cerebral cortex or the outer layer of the cerebrum is made of grey matter in which nerve cells are located. Different areas of the cerebral cortex function as the highest centres for sensations and activities; e.g. the somesthetic or general sensory area, motor area, visual area, auditory area and premotor area. Hypothalamus consists of scattered masses of grey matter in the white matter at the base of the brain. It contains nerve centres for temperature regulation, hunger, thirst and emotional reactions and the autonomic nervous system. It secretes neurohormones controlling the secretion of the anterior pituitary hormones. It synthesises the posterior pituitary hormones and also controls their release from the posterior pituitary into the blood.

The midbrain nuclei control muscle tone, and modify motor activities initiated by the cerebral cortex.

The hindbrain consists of cerebellum and brain-stem. Cerebellum contains centres for maintenance of muscle tone, posture and equilibrium and also for modulating movements initiated by the cerebral cortex. The brain-stem consists of medulla oblongata and pons varoli, and contains many centres for vegetative activities such as respiration, circulation and salivation.

The spinal cord has the grey matter at its centre and the white matter around it. Groups of nerve cells constitute spinal nuclei in the grey matter. Bundles of nerve fibres ascend or descend along the white matter forming the nerve tracts. The ascending tracts conduct nerve impulses coming from the peripheral tissues to the brain. The descending tracts conduct impulses down from the brain to be relayed ultimately to muscles and glands.

Peripheral nerves are made of many fibres. Afferent and efferent fibres conduct impulses respectively from and to the peripheral tissues. Efferent and afferent fibres are also motor and sensory fibres because they cause muscle movement.

Spinal nerves are mixed nerves and innervate peripheral tissues. In human being, thirty one pairs of these nerves originate from the spinal cord.

Cranial nerves originate from different regions of the brain and perform diverse functions. Twelve pairs of these nerves are present in the nervous system of man.

Nerve fibres terminate no other nerve fibres forming pathways. Motor end-plate, a specialised structure, occurs at the neuromuscular junction.

Receptors are structures at the end of sensory nerve fibres and acquaint the animal with changes inside its body and in the external environment.

Transmissions of nerve impulses involve electro-chemical process.

Spontaneous involuntary activities of the body are evoked by the stimulations of receptors and called reflexes. Reflexes may be unconditioned or conditioned.

The autonomic nervous system coordinate activities of visceral organs through the regulations of their smooth muscles and glands by its nerves. The AN system is

divided structurally as also functionally into two—the sympathetic and the parasympathetic system.

Senses for vision, hearing, smell and taste are called special senses. Eyes, ears, nose and tongue are special sense organs. Each of these organs has its characteristic structure and perceives a specific type of sense. Eyes, ears, nose and tongue function respectively as organs of vision, hearing (also balancing body), smell and taste.

## QUESTIONS

1. Fill in the blanks with correct words:

- (a) Sympathetic nerves dilate the pupil while parasympathetic nerves constrict it.
- (b) Junction between two neurons is called a synapse while the junction between a neuron and a muscle fibre is called a neuromuscular junction.
- (c) Taste of food evokes salivation by a unconditioned reflex while smell of food causes salivation by a conditioned reflex.
- (d) A spinal nerve is a mixed nerve while the olfactory nerve is a cranial nerve.
- (e) Sympathetic nerve fibres increase the heart rate while parasympathetic nerve fibres decrease the heart rate.
- (f) We see colour with the help of cones cells while vision in bright daylight depends on rods cells of the retina.
- (g) Preganglionic sympathetic fibres are generally shorter than postganglionic sympathetic fibres while preganglionic parasympathetic fibres are longer than postganglionic parasympathetic fibres.

2. Contrast between the following:

- (a) Rods and cones.
- (b) Conditioned reflex and unconditioned reflex.
- (c) Motor area and premotor area. *→ motor area*
- (d) Afferent neurons and efferent neurons.
- (e) Receptors and motor end-plates.
- (f) Cerebrum and cerebellum.
- (g) Preganglionic and postganglionic nerve fibres.
- (h) Mixed nerve and motor nerve.
- (i) Dorsal and ventral spinal nerve roots.
- (j) Ascending and descending nerve tracts.
- (k) Lateral and collateral sympathetic ganglia.
- (l) Adrenergic and cholinergic nerve fibres.

3. Explain the following:

- (a) Why does the nerve impulse flow more rapidly in myelinated nerve fibres than in the nonmyelinated fibres?
- (b) How does the middle ear help in hearing?
- (c) Why does vitamin A deficiency produce night-blindness?

*A drug given  $\rightarrow$  postganglionic sympathetic*

(d) Why do you soon stop smelling the perfume on your dress while persons approaching you still perceive its smell?

(e) Why do giant squids have very thick nerve fibres?

4. Match the items of Column A with the items of Column B:

Column A	Column B
(a) Somaesthetic area	(i) Pituitary
(b) Sympathetic nerve fibres	(ii) Node of Ranvier
(c) Sodium Pump	(iii) Muscle fibre
(d) Dorsal root ganglion	(iv) Posture and equilibrium
(e) Colour vision	(v) Cranio-sacral outflow
(f) Motor end-plate	(vi) Membrane potential
(g) Hypothalamus	(vii) Spinal nerve
(h) Parasympathetic nerve fibres	(viii) Cerebral cortex
(i) Saltatory conduction	(ix) Thoracico-lumbar outflow
(j) Cerebellum	(x) Rods
	(xi) Cones

5. Mark the wrong item in each series:

- (a) Eustachian tube; basilar membrane; taste buds; auditory ossicles.
- (b) Ciliary muscles; choroids; fovea; gustatory cells.
- (c) Dorsal root ganglion; preganglionic sympathetic neuron; lateral chain ganglia; postganglionic sympathetic neuron.
- (d) Sodium pump; polarised membrane; resting membrane potential; threshold stimulus.
- (e) Nonmyelinated nerve fibre; saltatory conduction; node of Ranvier; myelin sheath.

6. Answer the following questions briefly:

- (a) Compare the effects of sympathetic and parasympathetic nerves on the heart, pupil, blood vessels and blood pressure.
- (b) Describe a reflex arc with a diagram.
- (c) Compare the conduction of nerve impulse in myelinated and nonmyelinated nerve fibres.
- (d) Describe the course of sympathetic fibres from the central nervous system to the peripheral organ with a diagram.
- (e) Explain how the nerve impulse is transmitted across a synapse.
- (f) Describe with a diagram the course of parasympathetic fibres from the spinal cord to the peripheral organ.

## CONTROL AND COORDINATION

### ENDOCRINE SYSTEM

THE glands are secretory organs and are of two main types, viz. (i) exocrine glands and (ii) endocrine or ductless glands. Endocrine glands secrete active substances called **HORMONES**. Hormones do not reach their destinations through any duct. A hormone is secreted into the blood which distributes it all over the body, but the hormone acts only on target organs and tissues. The organs like pancreas and gonads are made of mixed tissues. One of their tissues is exocrine in nature and secretes a juice (e.g. the pancreatic juice) or form some cells (e.g. sperms and ova) which pass through specific ducts. But the rest of the organ is made up of endocrine tissue which secretes hormones (e.g. insulin from the pancreas, testosterone from testes) directly into the blood.

Hormones are **INFORMATIONAL MOLECULES**. They are secreted in response to changes in the environment inside or outside the body. Transported by blood, they reach the target organs, i.e. the organs for

which they are intended. Hormones may stimulate or inhibit specific biological processes in the target organs to modify their activities. Thus, acting as informational molecules, hormones regulate organs and tissues.

There is a considerable coordination between nerves and hormones. Synthesis and release of some hormones are regulated by nerves. On the other hand, hormones may also influence nerve activities. Hormonal coordination, therefore, plays an important role in regulating body functions.

Hormones secreted by endocrine glands do not act as enzymes. They do not catalyse specific chemical reactions. Unlike enzymes, they are not catalytic molecules at all. They may influence the synthesis, activation or inhibition of some enzymes in their target organs. Again, unlike enzymes, all hormones are not proteins—some hormones are macromolecular proteins or large peptides (e.g.

The action of hormone may be compared to those of nerves. You may recall that neurons also transmit information between different parts of the body and regulate body tissues or organs. But there are some basic differences between these two systems. As hormones have to be distributed by the blood circulation, they transmit information much more slowly than nerve impulses. Whereas a neuron elicits responses in the tissues within milliseconds, a hormone takes many seconds or minutes to produce a tissue response. Commensurate with this, hormones usually regulate processes where the response is not immediate but delayed, e.g. the hormonal control of body growth. Moreover, the hormonal action is generally less specific or precise, and more diffuse or widespread. The action of a neuron is more often limited to one or a few specific muscle fibres, gland cells or other neurons. But being distributed all over the body by blood, a hormone may simultaneously affect many cells, an entire organ or even several organs located wide apart from each other.

pancreatic and anterior pituitary hormones), but some others are only small peptides (e.g., posterior pituitary hormones), some are modified amino-acids (e.g., thyroid hormones), some are amines (e.g. adrenal medulla hormones) and still others are steroids (e.g. gonadal and adrenal cortical hormones). So, hormones differ from enzymes, both in action and chemical nature.

### Mammalian Endocrine System

The mammalian endocrine system (Fig. 39.1) consists mainly of the following organs and tissues: Hypothalamus, pituitary, thyroid, four parathyroids, two adrenals, two testes (male) or two ovaries (female), thymus, pineal, islet tissue of pancreas, and hormonal tissues on gastrointestinal tract. Besides, a nervous structure called hypothalamus of the brain is integrated with the endocrine system and also secretes hormones.

#### Hypothalamo-pituitary Axis

The hypothalamus is a part of the brain. It consists of several masses of the grey mat-

ter called HYPOTHALAMIC NUCLEI located in the white matter in the floor of the third cerebral ventricle of the brain (Fig. 39.2). Neurons of these hypothalamic nuclei control the pituitary gland. The latter is a small pea-shaped gland situated below the hypothalamus and connected to the brain by a stalk. The pituitary is divided into anterior, posterior and intermediate lobes.

The venous blood is collected from the region of hypothalamus by a portal vein which passes through the stalk and supplies the anterior lobe of pituitary. The hypothalamic neurons secrete several hormones called NEUROHORMONES into this blood. These reach the anterior pituitary through the portal blood and control the secretion of hormones by the cells of that gland. For example, THYROTROPIN-RELEASING HORMONE, CORTICOTROPIN-RELEASING HORMONE and GONADOTROPIN-RELEASING HORMONE of hypothalamus stimulate the anterior pituitary to secrete, respectively, the hormones called thyrotropin, corticotropin and gonadotropins; on the other hand, the



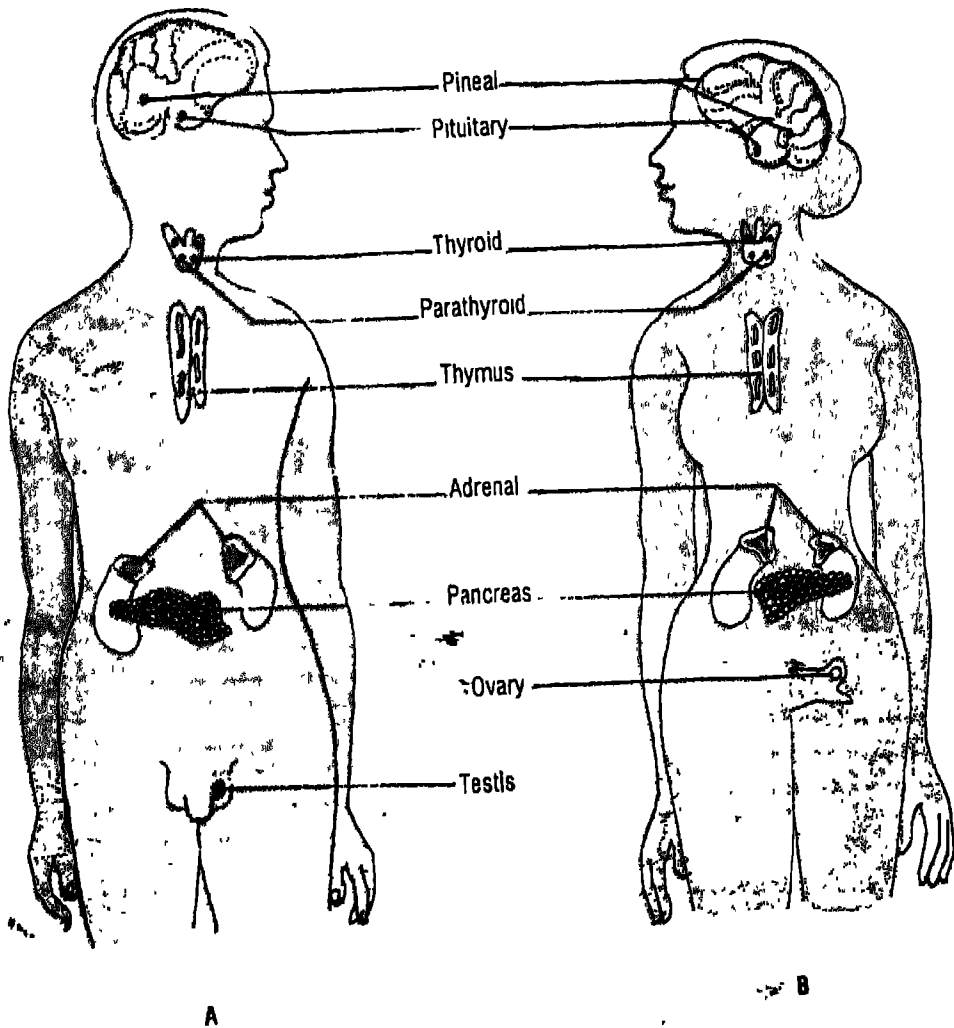


Fig. 39.1 Location of endocrine glands in human body A. Male and B. Female (diagrammatic)

hormone SOMATOSTATIN of the hypothalamus inhibits the secretion of the growth hormone from the anterior pituitary.

Some hypothalamic neurons send their axons through the pituitary stalks to the posterior pituitary. These neurons

synthesise two hormones called VASOPRESSIN and OXYTOCIN, which remain stored at their axon terminals inside the posterior lobe. When these neurons are properly stimulated, they release hormones into the blood inside the poster-

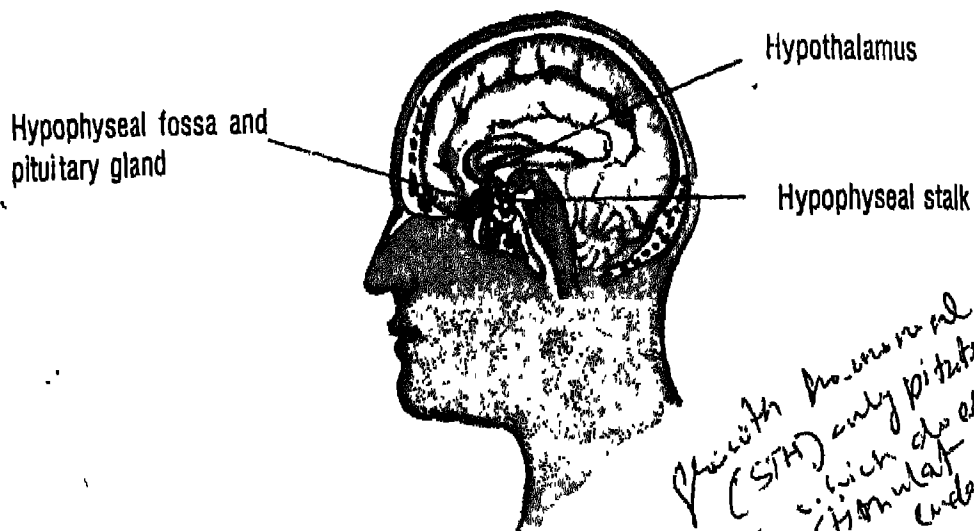


Fig. 39.2 Hypothalamo-pituitary axis in man

ior lobe. These are then carried out from the latter by blood and circulated in the body as the hormones of posterior pituitary.

The integrated and coordinated actions of hypothalamus and anterior lobe regulate the endocrine system to a large extent. The anterior lobe secretes six hormones from its different cells: (i) The growth hormone or SOMATOTROPIN (GH or STH) stimulates body growth, by stimulating retention of proteins and calcium in the body, synthesis and deposition of proteins in tissues, growth and elongation of long bones, and proportionate growth of muscles and visceral organs. The failure of secretion of growth hormone from an early age stops the growth of long bones and of the body prematurely; this makes the patient dwarf (DWARFISM). On the other hand, excessive secretion of this hormone from childhood turns the patient into a giant with abnormal elongation of all long bones (GIGANTISM). Over-

secretion of the growth hormone after adolescence causes abnormal elongation of long bones of arms, hands, legs and lower jaw, and a gorilla-like appearance (ACROMEGALY), but no giant stature. The growth hormone is probably the only anterior pituitary hormone which does not stimulate any other endocrine organ.

(ii) THYROTROPIN or THYROID-STIMULATING HORMONE (TSH) stimulates the growth of the thyroid and secretion of thyroid hormones. (iii) CORTICOTROPIN or ADRENOCORTICOTROPIC HORMONE (ACTH) of the anterior lobe stimulates the growth of adrenal cortex (outer layer of adrenal) and secretion of GLUCOCORTICOID hormones from it. (iv-vi) Three GONADOTROPINS or GONAD-STIMULATING HORMONES are also secreted by the anterior lobe viz. FOLLICLE-STIMULATING HORMONES (FSH), LUTEINIZING HORMONE (LH) and PROLACTIN (LTH). The FSH stimulates the testes in the male to produce sperms.

and the ovaries in the female to produce ova. It also stimulates ovaries to secrete female sex hormones called ESTROGENS. The LH (ICSH) stimulates the testes to secrete the male sex hormone—testosterone; LH stimulates the ovaries to secrete the female sex hormone called progesterone. Prolactin in the female stimulates the secretion of milk from the mammary glands after the birth of the child.

You have read that hypothalamic neurohormones control the secretions of all the anterior lobe hormones. The FEED-BACK MECHANISMS check any over-secretion of the hormones whose secretions are stimulated by the anterior lobe hormones. Whenever a target endocrine gland, controlled by a trophic or stimulating hormone of the anterior lobe, secretes excess of its hormone, the rise in the blood level of the latter inhibits further secretion of the stimulating hormone from the anterior lobe. This leads to a decline in the secretion of the target endocrine gland until the blood level of its hormone returns to normal. To put it in another way, the hormone of an endocrine gland, stimulated by the anterior lobe, is fed back to the latter and/or to the hypothalamus to inhibit the secretion of the stimulating hormone. For example, a rise in the blood level of thyroid hormones causes a feedback inhibition of thyrotropin secretion from the anterior lobe, similarly, corticotropin secretion is inhibited by the feedback effect of glucocorticoid hormones of the adrenal cortex. Such a coordination between the anterior pituitary and the endocrine glands controlled by it helps to maintain more or less constant blood levels of their hormones.

You may recall that the posterior pituitary secretes two hormones, VASOPRESSIN and OXYTOCIN. In fact, they are

synthesised in some hypothalamic neurons and remain stored in their axon terminals inside the posterior lobe. Whenever the blood osmotic pressure rises due to the loss of water from the body, these neurons are stimulated to release vasopressin into the blood in the posterior lobe. Vasopressin is also known as ANTIDIURETIC HORMONE (ADH) because it reduces the volume of urine by increasing the reabsorption of water from the urine in the distal convoluted tubules, collecting tubules and collection ducts in the kidney. This it does by rendering the walls of those tubules permeable to water. Failure of secretion of vasopressin leads to a reduced renal reabsorption of water and a consequent elimination of a large volume of very dilute (hypotonic) urine; this disease is known as DIABETES INSIPIDUS although the volume of urine is increased, no glucose appears in the urine of such patients. Besides its antidiuretic effect of reducing the urinary volume, vasopressin also enhances arterial blood pressure by causing constriction or narrowing of arterioles. The other posterior lobe hormone, viz. Oxytocin, is secreted into the blood when the hypothalamic neurons are stimulated either due to the distension of

The intermediate lobe of pituitary secretes a hormone called MELANOCYTE-STIMULATING HORMONE (MSH). It darkens the skin of many animals including fishes and amphibians. This results from a stimulation of synthesis of the black pigment melanin in the skin and also a dispersal of melanin granules to the processes of skin cells. In man, it has no such role.

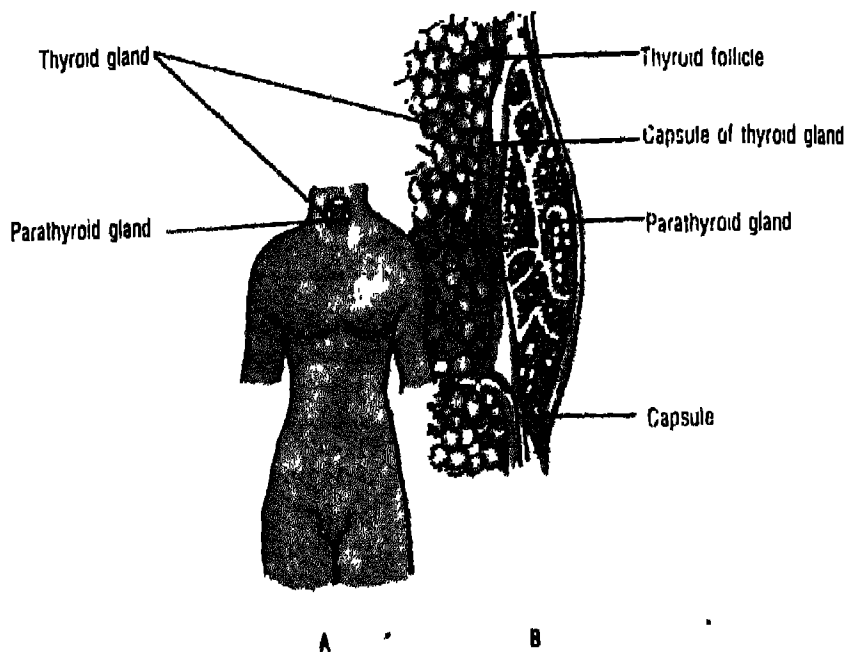


Fig. 39.3 Thyroid and parathyroid glands in man. A, location and B, internal structure (diagrammatic)

uterus by the full-term foetus or due to the sucking of the breast by the infant. Oxytocin contracts the smooth muscles of uterus and mammary glands. Uterine contractions, stimulated by oxytocin at the end of pregnancy, help in the child-birth. The oxytocin-induced contractions of the mammary gland muscles help in the flow of stored milk from the mammary glands to the mouth of the suckling infant. Therefore, oxytocin is also called 'milk ejection hormone' and 'birth hormone'.

### Thyroid

It is situated in the neck close to the trachea (Fig. 39.3). The gland consists of two elongated oval lobes joined by a narrow band called isthmus. It is a highly vascular

organ and contains many spherical or oval sac-like follicles. Cells lining the thyroid follicles secrete two thyroid hormones, thyroxine and triiodothyronine. Both are iodinated forms of an amino-acid called thyronine and remain stored in the jelly-like semifluid material (colloid) in the lumen of follicles. When necessary, the hormones are released from the colloid to the blood. You may recall that thyrotropin of anterior pituitary stimulates the synthesis and secretion of thyroid hormones. You may also recall that the principal biological role of iodine in the animal body is to form thyroid hormones. Functions: (i) Thyroid hormones greatly increase the metabolic rate of the body and, consequently, enhance heat produc-

tion and maintains BMR (basal metabolic rate). (ii) Thyroid hormones also promote growth of body tissues—both physical growth and development of mental faculties are stimulated. (iii) They stimulate tissue differentiation. Because of this action, they promote metamorphosis of tadpoles into adult frogs.

Disorders due to thyroid hormone imbalances: (i) Failure of thyroid secretion from infancy or childhood slows body growth and mental development and reduces metabolic rate markedly. The child remains physically stunted and mentally retarded. The body temperature, heart rate and blood pressure are lower than normal. The patient is pot-bellied and pigeon-chested and has a protruding tongue. This disease is called (CRETINISM). Normal growth and development may be restored in certain cases by an early administration of thyroid hormones.

(ii) Deficiency of thyroid hormones produces (MYXEDEMA in adults). The patient has a puffy appearance and lacks alertness, intelligence and initiative. The patient also suffers from low metabolic rate, slow heart rate, low body temperature and reproductive failure. Administration of thyroid hormones cures the symptoms.

(iii) You may recall that in mountainous regions, the dietary deficiency of iodine frequently produces thyroid enlargement (IODINE DEFICIENCY GOITRE), accompanied by cretinism or myxedema.

(iv) In GRAVE'S DISEASE or EXOPHTHALMIC GOITRE, a thyroid enlargement (goitre) is accompanied by a bulging of eyeballs (exophthalmos). The enlarged thyroid is overactive and secretes excessive amount of thyroid hormones. So, the goitre is associated with symptoms of

thyroid overactivity such as high metabolic rate, rapid heart rate, rise in body temperature, emaciation, nervousness, irritability, tremor and restlessness.

If young tadpoles are administered thyroxine, they metamorphose into frogs prematurely before their body growth is complete. They are thus changed into tiny frogs. On the other hand, feeding of antithyroid substances like thiourea to tadpoles, delays their metamorphosis. As they continue to grow without metamorphosis they become giant tadpoles.

Mexican axolotls are amphibians which ordinarily exist and even reproduce in the aquatic larval form without metamorphosis into the adult form, because they are born deficient in thyroid hormones. But on administration of thyroid hormones, they metamorphose into the terrestrial adult form.

### Parathyroids

These are four small glands situated very close to the thyroid (Fig. 39.1 & 39.3). They secrete a hormone called PARATHORMONE. They are under the feedback control of blood calcium level. A fall in blood calcium stimulates them to secrete parathormone. A rise in blood calcium inhibits parathormone secretion from them.

Parathormone increases the concentration of calcium ions in the blood plasma, because it mobilises more calcium from the bones to the plasma and reduces urinary elimination of calcium. It is secreted whenever the Plasma  $\text{Ca}^{2+}$  concentration falls and restores the  $\text{Ca}^{2+}$  concentration.

phenomenon in  
decrease P  
to normal in the plasma. On the other hand, it increases phosphate elimination in the urine and consequently lowers the phosphate concentration in the plasma. Thus, parathormone regulates the metabolisms of calcium and phosphorus.

**Disorders:** If the parathyroids fail to secrete sufficient amount of parathormone, the concentration of calcium ions fall abnormally in the plasma. This increases the excitability of nerves and muscles. Consequently, sustained contractions (tetany) of the muscles of larynx, face, hands and feet are produced. This disease is called PARATHYROID TETANY. On the other hand, the parathyroid tumours secrete excessive amount of parathormone. This causes increased mobilisation of bone minerals into the blood, softening of bones, rise in the concentration of calcium ions in the plasma, and deposition of calcium in

kidney tubules and other soft tissues.

### Adrenals or Suprarenals

Adrenals are two conical pyramid-shaped glands, one immediately above each kidney (Fig. 39.4). Each adrenal is made up of an outer layer called ADRENAL CORTEX and a central portion called ADRENAL MEDULLA. The cortex and the medulla secrete different hormones and are regulated in different ways.

**Adrenal cortex:** This part of adrenal is vitaly important for life and its destruction or removal kills the animals. It secretes a number of steroid hormones which are broadly classified into three groups, viz. glucocorticoids, mineralocorticoids and sex corticoids.

(i) MINERALOCORTICIDS are secreted from the outermost cellular layer of the adrenal cortex. Aldosterone is the principal mineralocorticoid in man, other mammals and birds. Mineralocorticoids regulate the metabolisms of sodium and potassium. Their secretion is stimulated by a fall in plasma  $\text{Na}^+$  concentration, or a rise in plasma  $\text{K}^+$  concentration, or a fall in circulating volume of blood. Aldosterone reduces the elimination of  $\text{Na}^+$  in the urine, sweat, saliva and bile by enhancing the active reabsorption of this ion from those fluids. It also increases the elimination of  $\text{K}^+$  in those fluids in exchange of the reabsorbed  $\text{Na}^+.$  By retaining more  $\text{Na}^+$  in the blood, it increases the reabsorption of water from the urine by the osmotic effect of  $\text{Na}^+.$  Due to the same reason, it increases the volumes of blood and other extracellular fluids.

(ii) GLUCOCORTICIDS such as CORTISOL are secreted from the middle cellular layer of the adrenal cortex. They regulate the metabolisms of carbohydrates, fats and proteins. You may recall that the

Metabolisms of calcium and phosphorus are also regulated by another hormone called CALCITONIN. It is secreted by some cells situated outside the follicles in the thyroid gland. Its secretion is also under the feedback control of the plasma  $\text{Ca}^{2+}$  concentration. But unlike parathormones, calcitonin is secreted when the concentration of  $\text{Ca}^{2+}$  rises in the blood plasma. Calcitonin then lowers the concentrations of both calcium and phosphate ions in the plasma by reducing their mobilisation from bones. Thus, it restores the normal concentration of these ions in the blood. The plasma calcium level is very effectively maintained by a balance between the activities of parathormone and calcitonin.

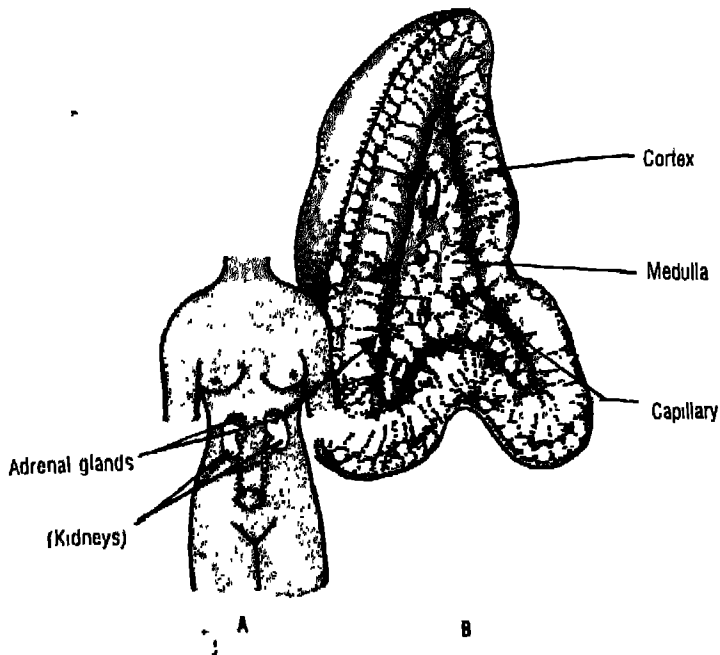


Fig. 39.4 Adrenal glands in man. A. location and B. internal structure (diagrammatic)

anterior pituitary hormone called corticotropin stimulates glucocorticoid secretion; glucocorticoids, on the other hand, exert a feedback inhibitory effect on corticotropin secretion.

(iii) SEX CORTICOIDS are secreted from both the middle and the inner layers of the adrenal cortex. Their secretion is believed to be stimulated by corticotropin of anterior pituitary. They include steroids which may stimulate the development of external sex characters of the male type such as the male pattern of distribution of body hair. Examples of sex corticoids are ANDROSTENEDIONE and DEHYDROEPIANDROSTERONE.

**Disorders:** (i) A destruction of adrenal cortex by diseases like tuberculosis produces

ADDISON'S DISEASE due to the deficiency of both glucocorticoids and mineralocorticoids. Symptoms include a bronze-like pigmentation of skin, low blood sugar, low plasma  $\text{Na}^+$ , high plasma  $\text{K}^+$ , increased urinary  $\text{Na}^+$ , nausea, vomiting and diarrhoea.

(ii) A tumour of the adrenal cortex may secrete too much cortisol to produce CUSHING'S SYNDROME. High blood sugar, appearance of sugar in the urine, obesity, wasting of limb muscles, rise in plasma  $\text{Na}^+$ , fall in plasma  $\text{K}^+$ , rise in blood volume and high blood pressure are observed in the patient.

(iii) Excessive secretion of aldosterone from an adrenal cortical tumour produces

Actions of adrenaline and noradrenaline are not identical in many tissues. Adrenaline dilates (widens) arterioles in the skeletal muscles but constricts (narrows) those in the skin and abdominal viscera; noradrenaline constricts arterioles in general to increase the total peripheral resistance against the flow of blood. Adrenaline increases both rate and force of heart beats; noradrenaline has little effect on the heart. Both increase arterial blood pressure, the former by enhancing the cardiac output and the latter by raising the peripheral resistance. Adrenaline relaxes the smooth muscles of gastrointestinal tract, urinary bladder and bronchioles, but contracts the sphincters of gastrointestinal tract and bladder; noradrenaline has no action on the bronchiolar muscles and only weak actions on the other smooth muscles. Adrenaline increases blood sugar and blood lactic acid levels; noradrenaline has very little effect on them. Both hormones increase heat production, metabolic rate and body temperature. Their coordinated actions help the body reactions in stress. This is why adrenal medulla is sometimes called the gland for 'fight, fright and flight'.

**ALDOSTERONISM** This disease is characterised by a high plasma  $\text{Na}^+$ , low plasma  $\text{K}^+$ , rise in blood volume and high blood pressure.

(iv) An excessive secretion of sex corticoids produces the male-type external sex characters such as beards and moustaches and male voice in women. The disease is called **ADRENAL VIRILISM**.

**Adrenal medulla:** This part of adrenal helps the body to combat against stress or emergency conditions. But it is not vital for survival and may be removed without causing death. Adrenal medulla secretes two hormones, viz. **adrenaline** and **noradrenaline**. The proportion of the two hormones varies from species to species; in man, much more adrenaline is secreted than noradrenaline. The secretion of these hormones is stimulated when nerve impulses reach the adrenal medulla through **sympathetic nerve fibres**. These hormones act on organs and tissues supplied by sympathetic fibres and produce effects like those of sympathetic stimulation. **Noradrenaline is also released at**

**sympathetic nerve terminals to transmit nerve impulses from them to smooth muscles and glands.** Both sympathetic nerves and adrenal medulla are stimulated in physical stress like fall in blood pressure or blood sugar, pain, cold or injury; both are also stimulated in emotional stress such as anger, fear and grief. All these indicate that the **adrenal medulla and the sympathetic nervous system function as a closely integrated system; this may be called sympathetico-adrenal system and is another instance of close coordination between nerves and hormones.**

#### **Pancreatic Islets**

The **pancreas** comprises both **exocrine** and **endocrine** parts. The **endocrine part** consists of small masses of hormone secreting cells called **ISLETS OF LANGERHANS**.

**INSULIN** and **GLUCAGON** are the hormones secreted by pancreatic islets. A rise in blood glucose level stimulates both the synthesis and the secretion of insulin. A rise in blood amino-acids may also



*Interstitial cells of Leydig = endocrine part of testis*

increase insulin secretion. The functions of insulin are:

- (i) Insulin increases the utilisation of glucose in tissues and facilitates the storage of glucose as glycogen in muscles and liver. By these actions, insulin lowers the blood sugar level.
- (ii) Insulin increases the synthesis of fat in the adipose tissue from fatty acids as well as glucose.
- (iii) It also reduces the breakdown and oxidation of fat.
- (iv) Insulin promotes protein synthesis in tissues from amino-acids.
- (v) It reduces catabolism of proteins in the body. Insulin is an anabolic hormone.

A second hormone called glucagon is also secreted by pancreatic islets. It increases the breakdown of liver glycogen to blood glucose and the formation of glucose from amino acids. So, it raises the blood sugar level and tends to cause the elimination of sugar in the urine.

Failure of insulin secretion produces DIABETES MELLITUS. In this disease, blood sugar is abnormally high and exceeds the renal threshold for glucose. Consequently, glucose appears in the urine. The utilisation of glucose is decreased; instead, catabolisms of fats and proteins are enhanced. Increased oxidation of fat produces ketone bodies such as acetoacetate and acetone. Also the blood cholesterol rises. The osmotic effect of glucose in the urine considerably increases the volume of urine. Thirst is enhanced due to urinary loss of water. Injuries take a long

time to heal and may turn into gangrenes. In extreme cases, the patient suffers from coma and may die. Administration of insulin reduces the blood sugar and checks other symptoms of diabetes.

### Endocrine Functions of Gonads

The gonads, viz. testes in males and ovaries in females, are mixed organs. They produce reproductive cells and secrete hormones which control reproductive organs. These hormones are collectively called sex hormones. They are secreted from near the age of puberty or sexual maturity.

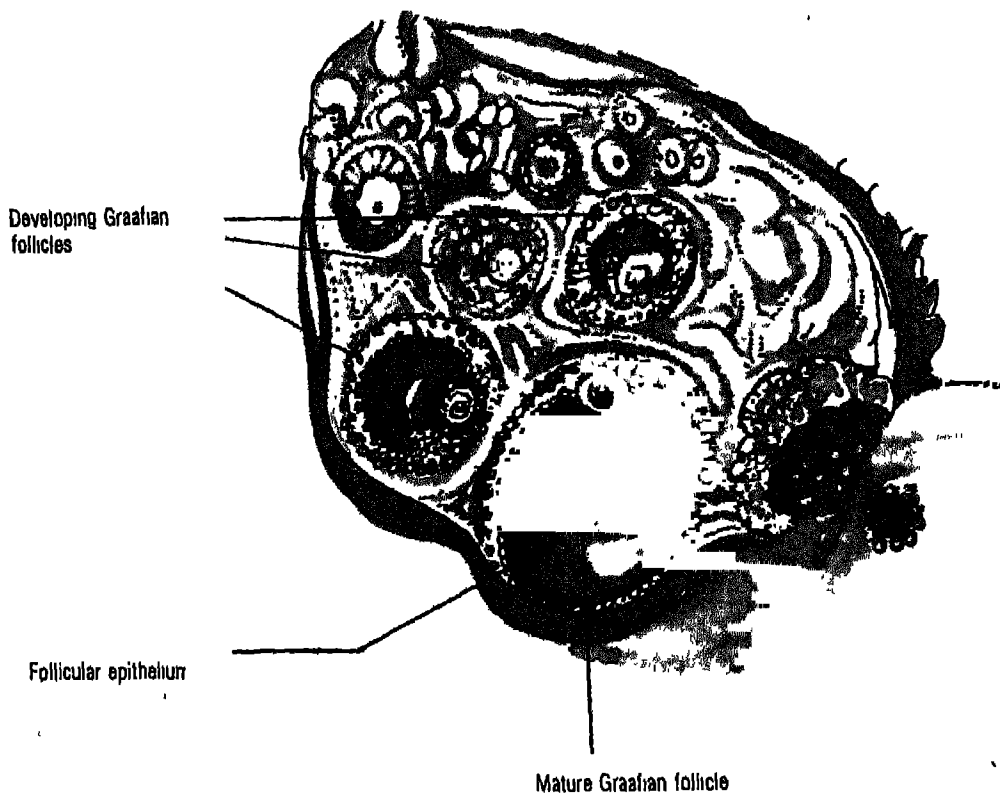
**Male sex hormone:** Testis secretes the male sex hormone called TESTOSTERONE. The endocrine part of testis consists of groups of cells located in the connective tissue around the sperm-producing (seminiferous) tubules. These cells are called INTERSTITIAL CELLS OF LEYDIG. The luteinizing hormone (LH) of anterior pituitary stimulates the interstitial cells to secrete testosterone; this is why LH is also known as INTERSTITIAL CELL STIMULATING HORMONE (ICSH). When the blood level of testosterone rises above normal, it exerts a feedback inhibitory effect on the anterior pituitary to stop further ICSH secretion. This normally prevents the over-secretion of testosterone.

**Functions:** Testosterone stimulates the growth and development of MALE SECONDARY SEX ORGANS such as the prostate, seminal vesicles and penis. It also stimulates and maintains their normal functions in reproduction. These organs are called secondary sex organs because they participate and help in reproduction but do not produce gametes. Testosterone stimulates the development of the external male sex characters such as beards, moustaches and low-pitch male voice in

CASTRATION or removal of testes causes failure of development of secondary sex organs and characters and removes the ability to reproduce. Castrated males called eunuchs were employed in royal harems in the middle ages as menials and guards. Choir boys were often castrated in medieval Europe to retain their high-pitch juvenile voice for singing. Castration changes the aggressive bull into a docile ox. The latter lacks the male character of aggressiveness due to testosterone deficiency. The docile ox can be conveniently used for ploughing and drawing of bullock carts.

man, and combs and wattles in cock. It also maintains these external characters. It also stimulates the formation of sperms in the testes. Testosterone promotes the growth of many body tissues including bones and muscles; this explains the body growth at puberty and a higher stature of the male body than the female body. Substances which stimulate the development of male sex characters, are called ANDROGENS. They include testosterone and some sex corticoids.

Disorders: The failure of testosterone secretion results in EUINUCHOIDISM. In this disease, secondary sex organs such as prostate, seminal vesicles and penis remain infantile and small in size and far to function. External sex characters like beards, moustaches and low-pitch male



**Fig. 39.5** Internal structure of ovary in human female showing Graafian follicles at different stages of development (diagrammatic)

PLACENTAL HORMONES

The human placenta secretes in the mother's blood several hormones such as estrogens, progesterone and HUMAN CHORIONIC GONADOTROPIN (hCG). Placental estrogens and progesterone participate in producing pregnancy changes in the female reproductive system. hCG enlarges the corpus luteum in the mother's ovary and stimulates it to secrete progesterone.

GASTROINTESTINAL HORMONES

These hormones are secreted from the gastrointestinal mucosa and regulate mainly the secretions and movements of the alimentary system. For example, GASTRIN is secreted from near the junction of stomach and duodenum; it stimulates secretion of gastric juice and movements of the stomach. SECRETIN is secreted from the intestinal mucosa; it stimulates the secretion of water and bicarbonates in the pancreatic juice and the bile, and inhibits the secretion and movements of the stomach. CHOLECYSTOKININ is also secreted from the intestinal mucosa; it stimulates the secretion of enzymes in the pancreatic juice and the contraction of gall bladder.

voice fail to develop. Spermatozoa fail to be produced. Administration of testosterone to the patient stimulates growth and development of secondary sex organs and characters.

Female Sex Hormones: Ovaries secrete steroid hormones which regulate the female reproductive organs. They are called female sex hormones; in chemical structure and functions, they belong to two types, viz. ESTROGENS and PROGESTERONE.

The ovary contains numerous sac-like cellular aggregates called ovarian follicles, each with a maturing ovum at its centre (Fig. 39.5). Cells of a maturing ovarian follicle (GRAAFIAN FOLLICLE) secrete estrogen. ESTRADIOL is the principal estrogen. Maturation of the Graafian follicle and secretion of estrogen from it are stimulated by the follicle-stimulating hormone (FSH) of anterior pituitary. The luteinizing hormone (LH) of anterior pituitary brings about a rupture of the Graafian follicle to release the ovum (ovulation), changes the

ruptured follicle into a yellow structure called CORPUS LUTEUM and stimulates the latter to secrete progesterone. In turn, high blood levels of estrogens and progesterone may cause feedback inhibition of the secretions of gonadotropins from the pituitary.

At puberty, estrogens stimulate the growth, maturation and functions of female secondary sex organs such as the uterus, Fallopian tubes and the duct system of mammary glands. Estrogens also develop and maintain external female sex characters like the high-pitch female voice and the female pattern of body hair distribution. Alternating actions of estrogens and progesterone cause some growth and functional changes in the female sex organs to be repeated cyclically in the non-pregnant female. The ovary secretes large amount of progesterone during pregnancy; progesterone brings about most of the pregnancy changes such as uterine growth, attachment of the embryo to the uterine wall, formation of a structure called

placenta holding the foetus on the uterine wall, and growth of secretory alveoli in mammary glands.

Table 39.1  
SOME IMPORTANT MAMMALIAN HORMONES

<i>Endocrine organ</i>	<i>Hormone</i>	<i>Principal actions</i>
Hypothalamus	Thyrotropin-releasing hormone	Thyrotropin secretion
	Corticotropin releasing hormone	Corticotropin secretion
	Gonadotropin releasing hormone	Secretion of pituitary gonadotropins
	Somatostatin.	Inhibition of growth hormone secretion
Anterior Pituitary	Growth hormone (GH)	Body growth
	Thyrotropin(TSH)	Thyroxine secretion
	Corticotropin (ACTH)	Glucocorticoid secretion
	Follicle-stimulating hormone (FSH)	Growth of ovarian follicle and estrogen secretion in females and spermatogenesis in males
	Luteinising hormone (LH)	Development of corpus luteum and progesterone secretion in females, testosterone secretion in males
	Prolactin	Milk secretion
Posterior pituitary	Vasopressin (ADH)	Hypertonic urine, arteriolar constriction
Thyroid	Oxytocin	Uterine contraction
	Thyroxine, triiodothyronine	Tissue metabolism, growth, differentiation
Parathyroids	Calcitonin	Fall in blood calcium
Adrenal cortex	Parathormone (PTH)	Rise in blood calcium
	Glucocorticoids (cortisol).	Carbohydrate, fat and protein metabolisms
	Mineralocorticoids (aldosterone)	Sodium and potassium metabolisms
Adrenal medulla	Sex corticoids	External sex characters
	Adrenaline and noradrenaline	Heart beat, blood pressure, contraction or relaxation of smooth muscles
Pancreatic islets	Insulin	Lowering of blood sugar, increase in glucose utilisation
	Glucagon	Rise in blood sugar.
Testis	Testosterone	Male secondary sex organs and external sex characters
Ovary	Estrogens	Female secondary sex organs and external sex characters
	Progesterone	Pregnancy changes in female sex organs.

## SUMMARY

Endocrine glands secrete hormones into the blood. Hormones are informational molecules. They regulate functions of other organs and tissues. Their actions are slower and more widespread than nerve impulses. They coordinate the activities of different organs and tissues. Unlike enzymes, they do not catalyse chemical reactions. Hormones may be proteins, peptides, amino-acids, catecholamines or steroids.

Neurons of hypothalamus secrete neurohormones such as thyrotropin-releasing hormone, corticotropin-releasing hormone, gonadotropin-releasing hormone and somatostatin. These are carried by a portal vein to the anterior pituitary and regulate secretions of its hormones like thyrotropin, corticotropin, gonadotropin and growth hormone. Some hypothalamic neurons called neurosecretory cells synthesise vasopressin and oxytocin which are released into the blood from their axon terminals in the posterior pituitary.

Of the anterior pituitary hormones, growth hormone stimulates body growth, thyrotropin stimulates the thyroid to secrete its hormones, corticotropin stimulates the adrenal cortex to secrete glucocorticoid hormones, follicle-stimulating hormone and luteinising hormones regulate the gonads and their hormone secretions, and prolactin causes milk secretion. Deficiency of growth hormone produces dwarfism while over-secretion of that hormone produces gigantism in the young and acromegaly in adults. Secretions of the trophic hormones of anterior pituitary are controlled by the negative feedback effects of the hormones of their respective target glands.

Of the posterior pituitary hormones, vasopressin increases renal reabsorption of water from the urine to make it hypertonic, and also raises the blood pressure by constricting arterioles. Oxytocin, another posterior lobe hormone, contracts the smooth muscles of uterus and mammary glands.

Thyroid secretes thyroxine and triiodothyronine. These thyroid hormones enhance the metabolic rate, promote body growth and tissue differentiation, and stimulate metamorphosis of tadpoles. Failure of thyroid secretion produces cretinism in the young age and myxedema in adults. Iodine deficiency goitre is also accompanied by reduced thyroid secretion. Grave's disease is characterised by a goitre secreting excess of thyroid hormones.

Parathyroids secrete parathormone which increases the blood calcium level by increasing the mobilisation of bone calcium and the renal reabsorption of calcium from the urine. Parathormone deficiency lowers the blood calcium and consequently produces sustained muscle cramps or tetany.

Adrenal cortex secretes three groups of steroid hormones. Mineralocorticoids such as aldosterone increase retention of  $\text{Na}^+$  in the body and elimination of  $\text{K}^+$  from the body. Glucocorticoids such as cortisol regulate the metabolisms of carbohydrates, proteins and fats. Sex corticoids develop external male sex characters. Failure of corticosteroid secretion in Addison's disease lowers the blood sugar and plasma  $\text{Na}^+$ , and raises plasma  $\text{K}^+$ . Over-secretion of glucocorticoids produces Cushing's syndrome with high blood sugar, obesity and high blood pressure. Over-secretion of aldosterone enhances plasma  $\text{Na}^+$ , blood volume and blood pressure in aldosteronism. Adrenal virilism is caused in women by over-secretion of sex corticoids, pro-

ducing beards, moustaches and the male voice.

Adrenal medulla secretes adrenaline and noradrenaline. Adrenal medullary hormones and the sympathetic nervous system function in an integrated and coordinated way as the sympathetico-adrenal system. Adrenal medullary hormones are secreted during stress, and they help in combating the stress condition.

Pancreatic islets secrete insulin on being stimulated by a rise in blood sugar or blood amino-acid level. Insulin lowers the blood sugar by increasing the utilisation of glucose and storage of glucose as glycogen in the tissue. Insulin deficiency produces diabetes mellitus with high blood sugar, excretion of sugar in the urine, increased urinary volume, high blood cholesterol and ketone body formation.

Testicular interstitial cells secrete testosterone. It stimulates growth and functions of secondary male sex organs, and the development of male external sex characters. Failure of testosterone secretion produces eunuchoidism with infantile male sex organs and undeveloped external sex characters. The Graafian follicle and corpus luteum of ovary secrete estrogens and progesterone, respectively. Estrogens stimulate the growth of female secondary sex organs. Progesterone controls pregnancy changes.

## QUESTIONS

1. Match the items of Column A with those of Column B:

<i>Column A</i>	<i>Column B</i>
(a) Acromegaly	(i) Luteinising hormone
(b) Vasopressin	(ii) Diabetes mellitus
(c) Ovulation	(iii) Thyroxine
(d) Spermatogenesis	(iv) Prolactin
(e) Insulin	(v) Oxytocin
(f) Cretinism	(vi) Growth hormone
(g) Aldosterone	(vii) ACTH
(h) Child birth	(viii) Follicle stimulating hormone
(i) Glucocorticoids	(ix) Adrenaline
(j) Milk secretion	(x) Sodium metabolism
	(xi) Diabetes insipidus

2. Mark the wrong item in each series:

- Growth hormone; TSH; vasopressin; LH.
- Goitre; cretinism; dwarfism; myxedema.
- Oxytocin; somatostatin; gonadotropin releasing hormone; corticotropin releasing hormone.
- Glucocorticoids; mineralocorticoids; sex corticoids; corticotropin
- FSH; TSH; prolactin; LH.

3. Distinguish between:

- Diabetes mellitus and diabetes insipidus.
- Exophthalmic goitre and iodine deficiency goitre
- Follicle stimulating hormone and luteinising hormone.

(d) Glucocorticoids and mineralocorticoids.

(e) Estrogens and progesterone.

(f) Vasopressin and oxytocin.

(g) Somatotropin and somatostatin.

4. Fill in the blanks with correct words:

(a) Corticotropin stimulates the growth of the Adrenal and the secretion of Glucocorticoids from it.

(b) Secretion of milk is stimulated by Prolactin while ejection of milk is stimulated by Oxytocin.

(c) Diabetes insipidus results from a deficiency of Vasopressin while diabetes mellitus is caused by a deficiency of Insulin.

(d) Growth of female secondary sex organs is stimulated at puberty by Estrogens while growth of male secondary sex organs is stimulated by Testosterone.

(e) Deficiency of growth hormone from childhood produces the disease called 侏儒症 while over secretion of that hormone from childhood causes 巨人症.

(f) Urinary loss of  $\text{Na}^+$  is reduced by the hormone Angiotensin II while the  $\text{Ca}^{2+}$  concentration is raised in the plasma by Parathyroid hormone.

(g) Reabsorption of water from the urine is increased by the hormone ADH while reabsorption of  $\text{Na}^+$  from the urine is enhanced by Angiotensin II.

5. Write the names and sources of the hormones regulating the following:

(a) Uterine changes in pregnancy.

(b) Urinary elimination of water.

(c) Metamorphosis of tadpoles.

(d) Plasma  $\text{Ca}^{2+}$  level.

(e)  $\text{Na}^+$  and  $\text{K}^+$  metabolisms.

(f) Blood sugar level.

(g) Secretion of growth hormone.

(h) Leydig cells of testis.

(i) Milk secretion.

(j) Uterine contractions at childbirth.

6. Explain the following:

(a) Insulin lowers the blood sugar level.

(b) Hypothalamus and pituitary function as an integrated and coordinated system.

(c) Body growth is greatly accelerated at puberty in the male.

(d) Adrenal medulla and the sympathetic nervous system function as a closely integrated system.

(e) Pituitary regulates the reproductive system in both sexes.

(f) Feed-back systems control the blood level of many hormones.

7. Describe the physiological functions and disorders of thyroid hormones.

8. Write briefly about the endocrine gland which helps to combat stress.





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## ANIMAL REPRODUCTION

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REPRODUCTION is an important characteristic of living organisms. It is the process by which an organism produces young individuals of its own species. It thus maintains the continuity of the species. There are two modes of reproduction in animals—asexual and sexual.

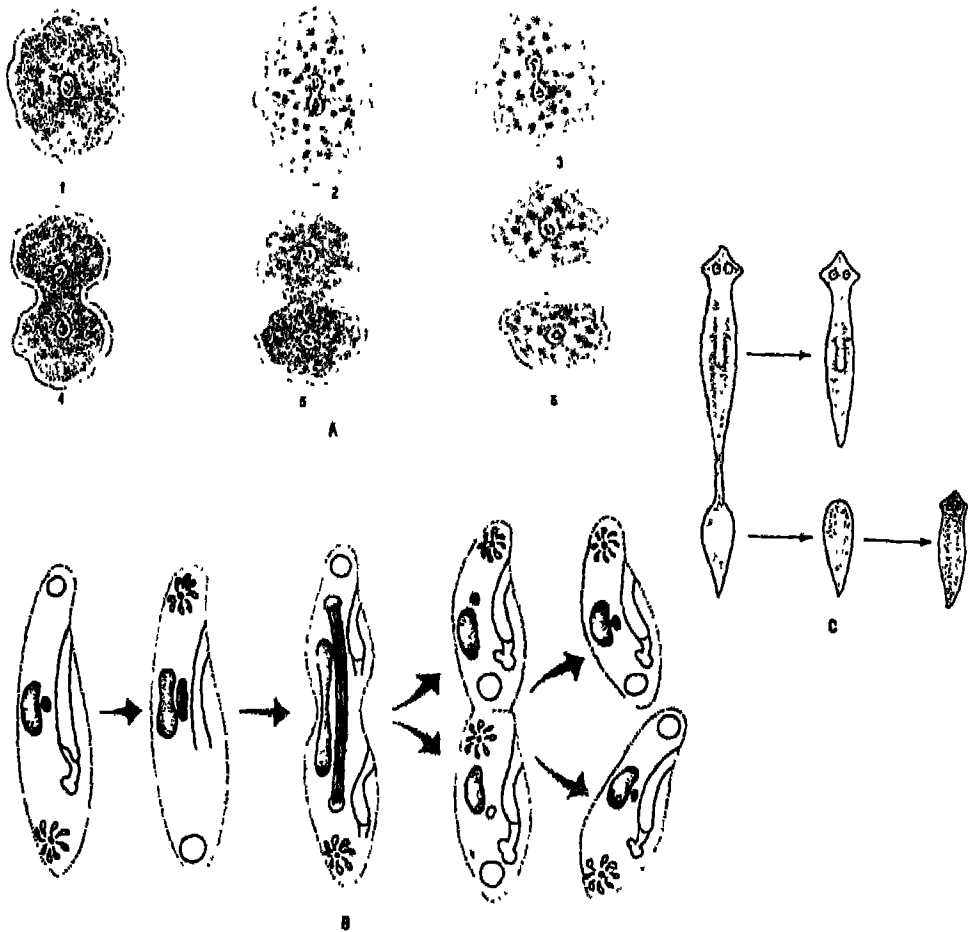
### Asexual Reproduction

In this type of reproduction, the participation of two organisms is not required. It also does not involve formation or union of sex cells. Most common forms of asexual reproduction in animals are fission (Fig. 40.1) and budding (Fig. 40.2). Sometimes, the body of a single organism divides into more than one new organism by a process called FISSION. Various protozoa, *Hydra* and some flatworms can reproduce by fission of their bodies. Fission may be BINARY (e.g. *Amoeba*, *Paramoecium*, *Planaria*) where the parent organism divides into two halves, each forming an independent daughter organism. It may be MULTIPLE when the parent body divides into many daughter organ-

isms (e.g. malarial parasite). The binary fission may be longitudinal or transverse, e.g. transverse fission in *Planaria* (Fig. 40.1C). *Hydra* may reproduce vegetatively by EXOGENOUS BUDDING (Fig. 40.2). A conical outgrowth or bud grows externally on the surface of the body wall by the proliferation and differentiation of some of its ordinary vegetative cells. The bud gradually develops some tentacles around the oral aperture at its free end, and a central cavity continuous with the body cavity (coelenteron) of the organism. A constriction then appears at the fixed end of the bud. It deepens to pinch off the bud from the body wall of the parent organism. The freed bud now forms a full-fledged independent *Hydra* and anchors itself to a surface by a basal disc formed at its bottom end.

### Sexual Reproduction

Males and females of the species are responsible for this form of reproduction. They produce cells specialised for reproduction which are called sex cells or GA-

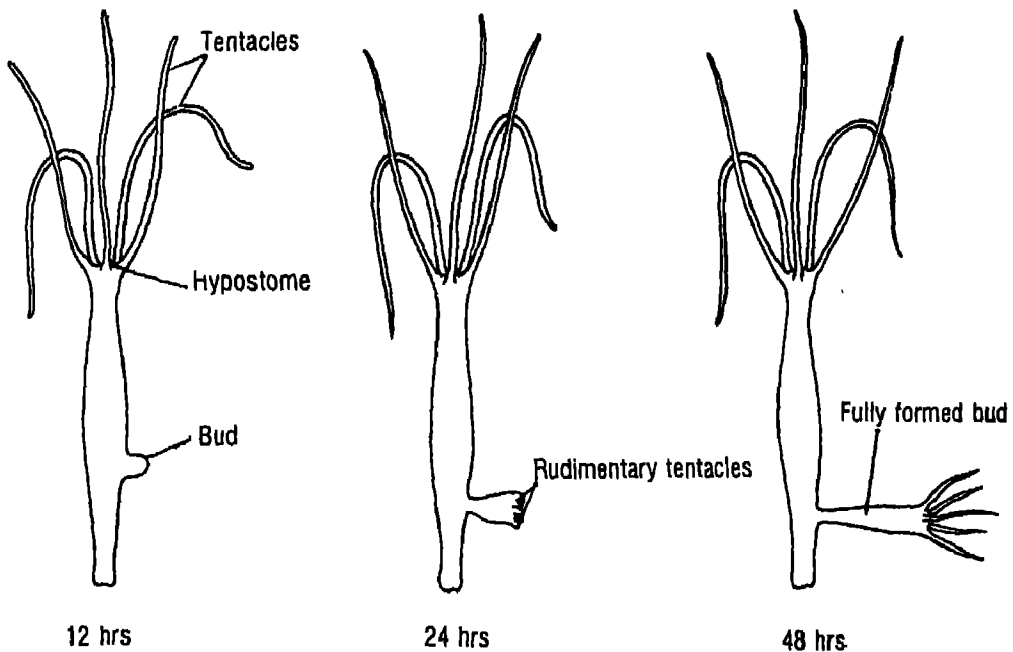


**Fig. 40.1** A. Binary fission in *Amoeba* (1 to 6). (Note that the division of the cell body takes place after the division of the nucleus); B. Stages of fission in *Paramaecium*; C Transverse fission in *Planaria*

**METES.** The male sex cells are called **SPERM CELLS** and female sex cells are known as **OVA** (sing, **OVUM**). The fusion of one sperm cell with an ovum produces, a **ZYGOTE**. The single-celled zygote contains all the chromosomes originally present in the two gametes. Repeated mitosis of the zygote forms a multicellular **EMBRYO** which gradually develops into a full-

grown animal.

**ISOGAMY** is the union of two cells of identical structures. This occurs in many unicellular organisms such as *Monocystis*. But in many animals, union takes place between two gametes of different sizes and structures. One of the gametes is smaller in size, motile and deficient in stored nutrients; it is called male gamete,

Fig. 40.2 Bud formation in *Hydra*

**MICROGAMETE** or **SPERM**. The other is much larger in size, non-motile and laden with stored nutrients; it is called female gamete, **MACROGAMETE** or **OVUM**. The union between two such dissimilar gametes is known as **ANISOGAMY**.

Sperms and ova are produced in higher animals by organs called **GONADS**. The male gonad called **TESTIS** produces sperms; the female gonad called **OVARY** produces ova. In earthworm, leech and tapeworm, the same animal carries both testes and ovaries. They are called **BISEXUAL ANIMALS (HERMAPHRODITES)**. Most vertebrates and many invertebrates are unisexual animals, the male animal carries only testes and the female possesses only ovaries. For sexual reproduction, higher animals possess highly evolved reproductive systems.

### Parthenogenesis

This is a special form of reproduction in some of the animals which normally carry out sexual reproduction. It is the development of a fully formed animal directly from an unfertilised ovum. In honey bees, queen bees and worker bees are developed from fertilised ova. Drones (males) are produced parthenogenetically.

### Mammalian Reproductive System

Sexes are separate in mammals—males and females. Each sex possesses reproductive organs, reproductive ducts and accessory structures. The primary sex organs are testes (sing. testis) in males and ovaries in females. Besides producing gametes, they also secrete sex hormones. Their growth, maintenance and functions are regulated by gonadotropins of the an-

terior pituitary. The organs which perform important functions in reproduction but neither produce gametes nor secrete sex hormones, are called **SECONDARY SEX ORGANS**. These include the prostate, seminal vesicles, vas deferens and penis in males, and the Fallopian tubes, uterus, vagina and mammary glands in females. **ACCESSORY OR EXTERNAL SEX CHARACTERS** are those distinctive structures or characters which distinguish the two sexes of a species in appearance but do not directly play any role in reproduction. In human beings, these include low-pitch and high-pitch voices of man and woman, respectively, and male and female patterns of facial and body hair distributions. The details of human reproductive system are described below.

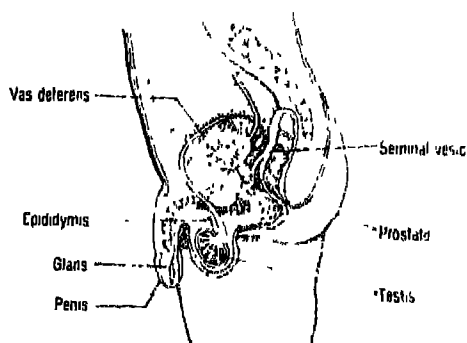
### *Male Reproductive System*

The male reproductive system of mammals consists of paired testes, several accessory glands, a duct system and a mating organ called the penis (Fig. 40.3). **TESTIS** is the primary male sex organ. It produces spermatozoa and secretes the male sex hormone testosterone. The human testis measures about 4 cm, 3 cm, and 2.5 cm, respectively, in length, thickness and

width. It is covered by thick connective tissue sheaths. In man, both testes normally remain suspended in a pouch called **SCROTUM** outside the abdominal cavity. This keeps the testes at a cooler temperature than the body temperature—this is essential for the maintenance and function of the spermatogenic tissue of the testes. In some seasonally breeding mammals, testes descend into the scrotum in the breeding season but ascend back into the abdomen in the non-breeding state.

Each testis contains numerous tiny, highly convoluted tubules, called **SEMINIFEROUS TUBULES** (Fig. 40.4). They constitute the spermatogenic tissue of the testis. Cells lining these tubules give rise to spermatozoa which are released into the lumen of the tubule. Groups of polyhedral cells, called **INTERSTITIAL CELLS OF LEYDIG**, are located in the connective tissue around the seminiferous tubules. They constitute the endocrine tissue of the testis. Leydig cells secrete testosterone into the blood. Seminiferous tubules unite to form several straight tubules which open into irregular cavities in the posterior part of the testis. Several tubes called **VASA EFFERENTIA** arise from the cavities and conduct spermatozoa out from the testis.

The duct system consists of tubes which conduct sperms from the testes to the outside. It starts with vasa efferentia which arise from each testis and become confluent to form a folded and coiled tube called **EPIDIDYMISS** behind each testis. The epididymis stores the sperms temporarily. From each epididymis, a partially coiled tube called **VAS DEFERENS** ascends into the abdomen, passes over the urinary bladder and receives the duct from the seminal vesicle, behind the urinary bladder to form an **EJACULATORY DUCT**. The



**Fig. 40.3** Male reproductive system of human

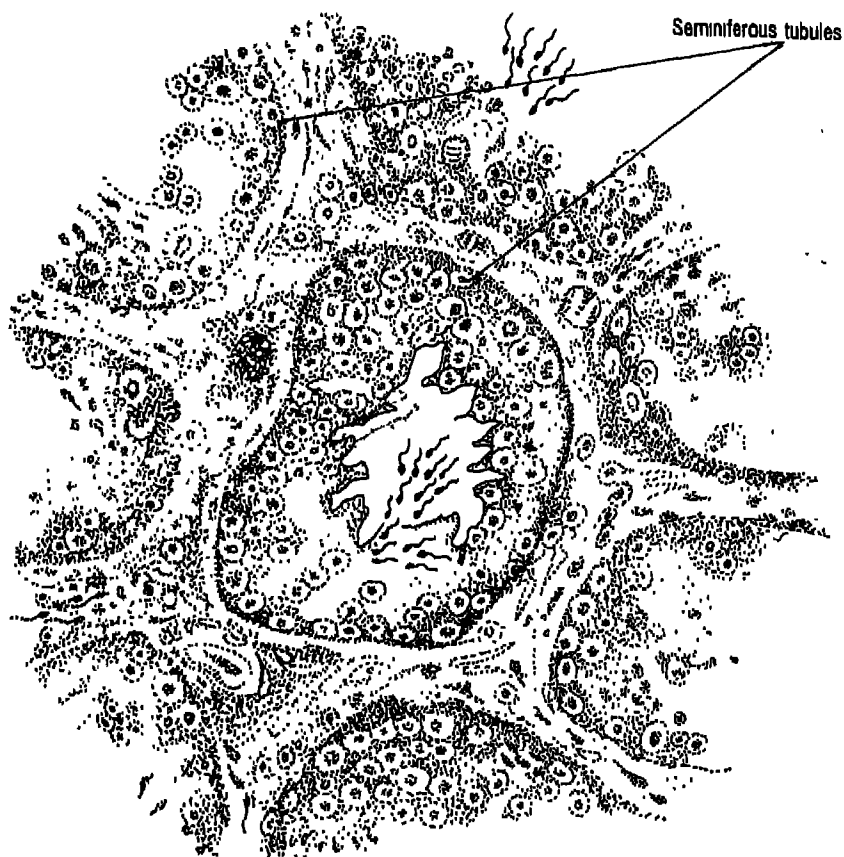


Fig. 40.4 A transverse section of testis of an adult human male, (diagrammatic)

latter passes through the prostate to open into the URETHRA shortly after its origin from the urinary bladder. The urethra receives the ducts of the prostate and Cowper's glands, passes through the penis and opens to the outside. The PENIS is a muscular organ used in mating. It is made up of a spongy muscle tissue which, when filled with blood, causes stiffening and

erection of the organ.

ACCESSORY or SECONDARY GLANDS include a prostate, two seminal vesicles and two Cowper's glands. The PROSTATE is situated around the first part of the urethra and secretes its fluid into the latter. SEMINAL VESICLES are situated behind the bladder. They are narrow, long pouches with muscular tissue on their wall. Their

secretion enters the vas deferens through their ducts. COWPER'S GLANDS are situated beneath the bladder and behind the urethra, into which their ducts open. SEMEN is the fluid mixture of spermatozoa and the secretions of these accessory glands, which comes out through the urethra. The accessory or secondary sex glands secrete juices which provide the fluid medium for transporting spermatozoa, supply nutrients to them and maintain their viability and motility by providing the proper pH and ionic strength.

The duct system, accessory glands and penis are secondary male sex organs. Their growth, maintenance and functions are promoted by testosterone secreted by Leydig cells. On the other hand, the growth, maintenance and functions of seminiferous tubules and Leydig cells are regulated, respectively, by FSH and LH of anterior pituitary.

### *Female Reproductive System*

The female reproductive system consists of two ovaries, oviduct, uterus, cervix, vagina (Fig. 40.5) and accessory genital glands and the mammary glands. The OVARY is the primary female sex organ. It produces ova and secretes the female sex hormones, viz. estrogens and progesterone. The human ovary measures about 3 cm, 2 cm, and 1 cm, respectively, in length, breadth and thickness. It has an ovoid shape, is situated near the kidney and remains attached to the abdominal wall by ligaments. Each ovary contains many large and small, spherical or oval, sac-like masses of cells; these cell masses are called OVARIAN FOLLICLES or GRAAFIAN FOLLICLES (Fig. 40.6). They occur at various stages of their development and maturation in the ovary. Each ovarian follicle carries a large, centrally placed ovum

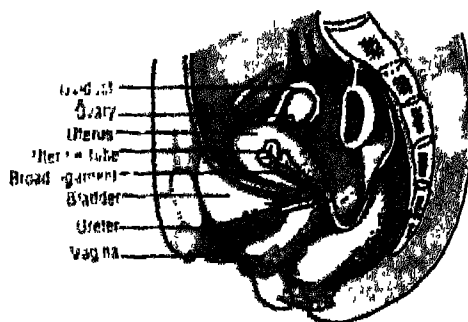
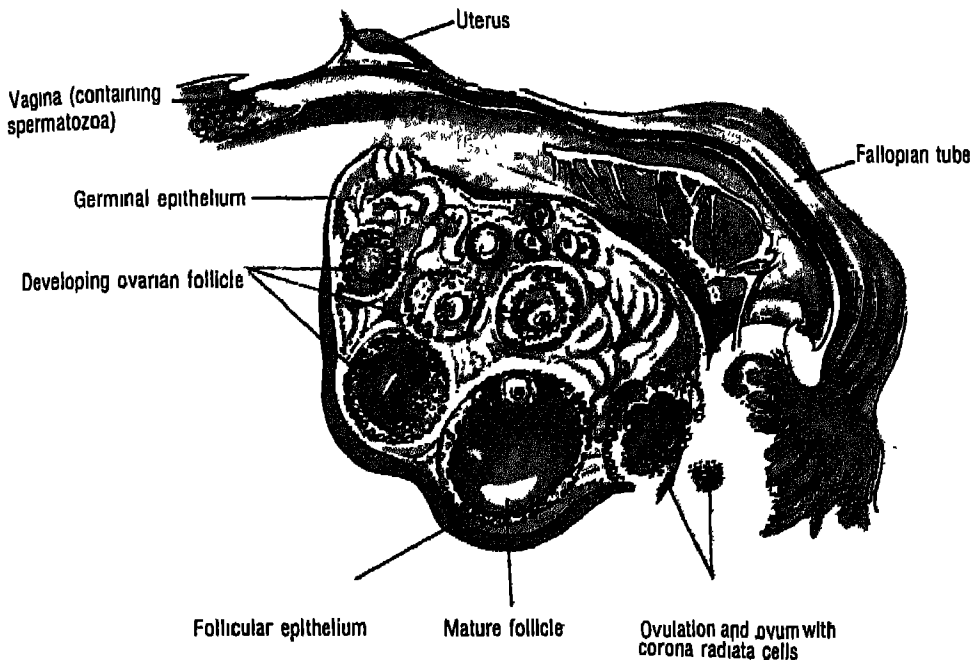


Fig. 40.5 Female reproductive system of human

surrounded by many layers of granular cells. In a maturing follicle, these cells secrete estrogens in the blood. The ovary may also contain a large mass of big, conical, yellow cells. This structure is called CORPUS LUTEUM. The latter is formed from a ruptured Graafian follicle after its ovum has been released. Cells of the corpus luteum secrete progesterone in the blood.

The duct system consists mainly of two Fallopian tubes, a uterus and a vagina (Fig. 40.6). The spermatozoa received from the male moves upward to the Fallopian tubes. The ovum may be fertilised by a sperm in the Fallopian tube. The fertilised ovum starts dividing and at the blastocyst stage gets implanted on the wall of uterus and develops into the growing foetus during pregnancy. Each Fallopian tube is a muscular tube starting near the ovary from an open fimbriated funnel-shaped end. The tube measures about 10 cm in length in human females. Its lumen is lined by ciliated epithelial cells. The ovum, released from the ovary, enters into the Fallopian tube through its open fimbriated end; it is then conveyed by the ciliary



**Fig. 40.6** Sectional view of duct system and ovary of human female (diagrammatic)

movements of the epithelial cells towards the uterus. The two Fallopian tubes open into a strongly muscular sac called **UTERUS**. The latter is situated above and behind the urinary bladder and remains attached to the body wall by ligaments. The foetus grows in the uterus during pregnancy. The human uterus measures about 8 cm, 5 cm, and 2 cm, respectively, in length, breadth and thickness. Its lumen is lined by a mucous membrane called **ENDOMETRIUM** which is highly vascular and very rich in glands. The uterus opens into an elastic muscular tube called **VAGINA**. The latter measures about 8 cm in length and opens to the exterior between the urethra and the anus. The vagina receives

the semen from the male during mating. During child birth, it conveys the child to the outside.

You may recall that the ovary is regulated by pituitary gonadotropins. The FSH of anterior pituitary stimulates the growth, development and hormone secretion of the Graafian follicle and maturation of the ovum. The LH of anterior pituitary stimulates rupture of the mature Graafian follicle and liberation of the ovum from it (ovulation). It also changes the ruptured follicle into the corpus luteum and stimulates the secretion of estrogen and progesterone from it. On the other hand, estrogens and progesterone secreted by the ovary control the growth

and functions of female secondary sex organs.

Most birds possess only the left ovary and the left oviduct for conveying the ovum released from the ovary. The right ovary and the right oviduct are normally reduced to rudimentary vestiges. The avian ovary does not form a corpus luteum from the ruptured ovarian follicle which undergoes rapid shrinkage. The uterus is absent. Instead, the left oviduct leads to a swollen tube called shell gland. When the egg reaches here through the oviduct, the shell gland deposits calcium salts on it to form the egg shell.

### Gametogenesis

Gametogenesis is the formation of gametes for sexual reproduction (Fig. 40.7). Gametogenesis is carried out in the gonads; spermatogenesis is the production of sperms in the testis, and oogenesis is the formation of ova in the ovary.

### Spermatogenesis

Spermatogenesis takes place in the seminiferous tubules of testes by repeated divisions of spermatogonia (Fig. 40.8). Spermatogenesis occurs in four stages: SPERMATOCYTOGENESIS, MEIOSIS I, MEIOSIS II and SPERMIOGENESIS. The first three stages involve divisions of the spermatogenic cells. Although the nuclear division occurs in each of these three stages, cytokinesis or cytoplasmic division is not complete in the daughter cells in any of these three divisions. So all the daughter cells, produced from a single mother cell by these three divisions, remain interconnected by their cytoplasm,

but they possess separate nuclear materials. The last stage, i.e. spermiogenesis, involves no cell division. It is only during spermiogenesis that maturing interconnected gametes separate from each other.

SPERMATOGONIA are diploid ( $2n$ ) cells on the wall of seminiferous tubules. Each spermatogonium divides mitotically to form two PRIMARY SPERMATOCYTES (Fig. 40.7), diploid and interconnected by their cytoplasm. However, the interconnections have not been shown in Fig. 40.7 for the sake of simplicity. Both the primary spermatocytes then undergo meiosis I, each giving rise to two haploid ( $n$ ) SECONDARY SPERMATOCYTES. All four secondary spermatocytes from a single spermatogonium remain interconnected by their cytoplasm. Then, the secondary spermatocytes undergo meiosis II, and producing two haploid cells called SPERMATIDS. Consequently, each spermatogonium gives rise to eight interconnected spermatids. The latter then undergo transformation, each into a haploid and flagellated spermatozoon, by the process of spermiogenesis. During the process spermatozoa separate from each other and are released free in the lumen of the seminiferous tubule. They are carried to the epididymis where they acquire motility during their temporary storage. Testosterone seems to promote their motility.

The growth and maintenance of seminiferous tubules as well as spermatogenesis require a lower temperature than that inside the abdomen. This is provided by the descent of the testis from the abdomen to the scrotum. Failure of testes to descend into the scrotum causes the retention of testes inside the abdomen and expose them to high abdominal temperature. Spermatogenesis cannot



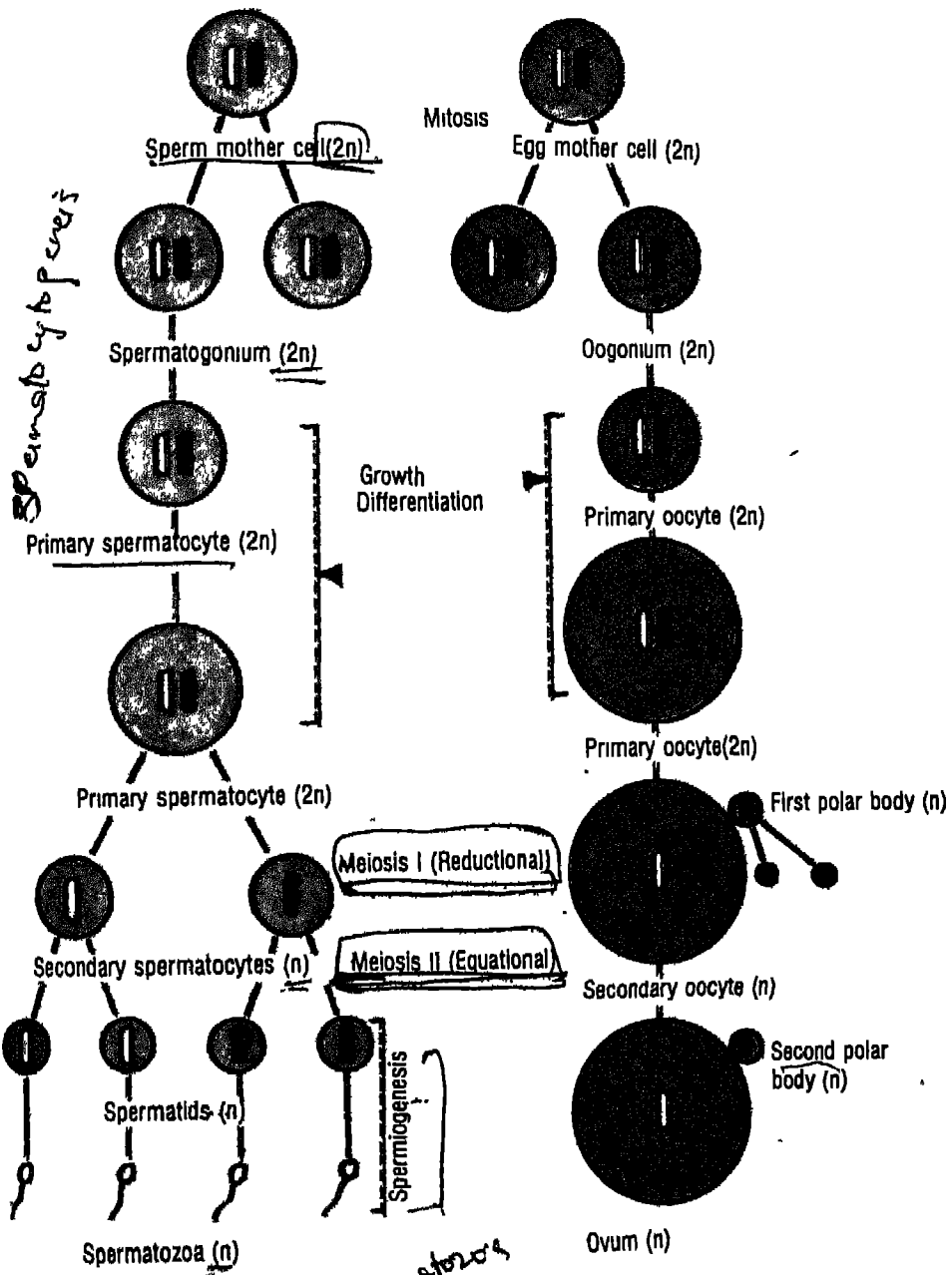


Fig. 40.7 Gametogenesis in animals (diagrammatic): A. Spermatogenesis and B. Oogenesis

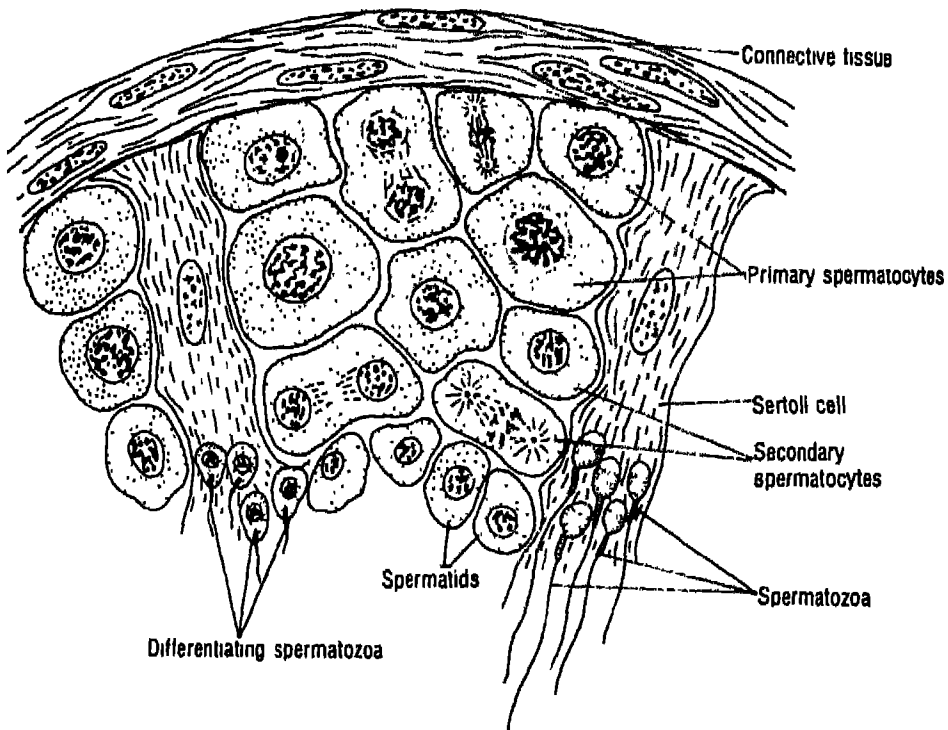


Fig. 40.8 Cross-section through a small part of seminiferous tubule of testis to show some stages of spermatogenesis (diagrammatic)

take place at this temperature and sterility results. The FSH of anterior pituitary promotes the descent of testes into the scrotum.

**HUMAN SPERMATOZOOM** is a long, flagellated, motile cell. It has a flat oval head, a narrow neck, a middle piece and a long narrow tail ending in flagellum (Fig. 40.9). The head contains the nucleus. The Golgi body is modified to form a sheath called **ACROSOME** on the first part of the head. Several fine fibrils or microtubules run from a centriole at the neck to the end of the tail through the middle piece and are encircled by a spiral sheath. A second cen-

trirole is situated at the junction of the middle piece with the tail. Flagellar movements enable the sperm to ascend along the female reproductive tract. You will learn more about the differentiation, structure and function of the mammalian spermatozoa in the next chapter. Sterility results if the sperms are immobile, structurally abnormal or poor in number in the semen.

#### Oogenesis

Oogenesis or formation of ovum is carried out in the Graafian follicle of the ovary. The maturing Graafian follicle contains a

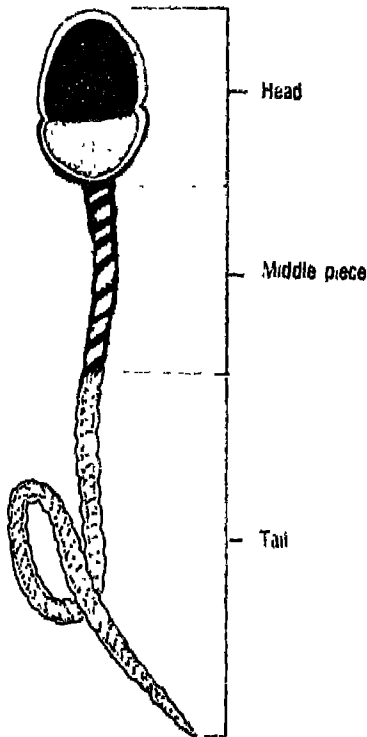


Fig. 40.9 Structure of a human spermatozoon

diploid (2n) PRIMARY OOCYTE at its centre. It undergoes meiosis I to produce two haploid (n) cells; the larger one is a SECONDARY OOCYTE and the smaller one is called POLAR BODY (Fig. 40.7). During meiosis I of the primary oocyte, the Graafian follicle comes to the ovarian surface. Immediately after meiosis I, it ruptures to eject the secondary oocyte near the open end of the Fallopian tube. As the secondary oocyte is carried down the Fallopian tube by ciliary movements of its cells, the oocyte already starts its meiosis II but meiosis II remains suspended at its meta-phase until a sperm enters the secondary oocyte. This recommences the suspended meiosis II which divides the secondary

oocyte into a haploid mature ovum and a second polar body. Before the nucleus of the mature ovum gets organised after meiosis II, its nuclear material mixes with that from the head of the sperm entering the ovum. Thus, a FERTILISED OVUM results with diploid (2n) chromosome number. Further details of the fertilisation process in mammals have been dealt in chapter 41.

You should note that whereas a primary spermatocyte gives rise to four spermatozoa, only one ovum is produced from a primary oocyte. This provision for a far higher number of spermatozoa is commensurate with the fact that the task of searching out the ovum in the female reproductive tract has been left to the sperms; on the contrary, the number of ova produced at a time has to be limited for restricting the number of offspring within the capacity of the mother to bear and rear them.

### Menstrual Cycle

Throughout the reproductive part of life, the mammalian female produces ova at intervals from the ovary. Each time the ovum starts maturing, the secondary sex organs also commence some growth changes to prepare for the reception of the expected fertilised ovum and the continuation of the anticipated pregnancy. The ovum, unless fertilised by a sperm, remains viable in the female reproductive tract for only a couple of days after ovulation. So, if the ovum fails to be fertilised within this period, pregnancy is not expected immediately and the female reproductive organs undergo some temporary involution with break-down of their overgrown tissues. Then, the ovary starts preparing for the maturation and ovulation of the next ovum and the secondary

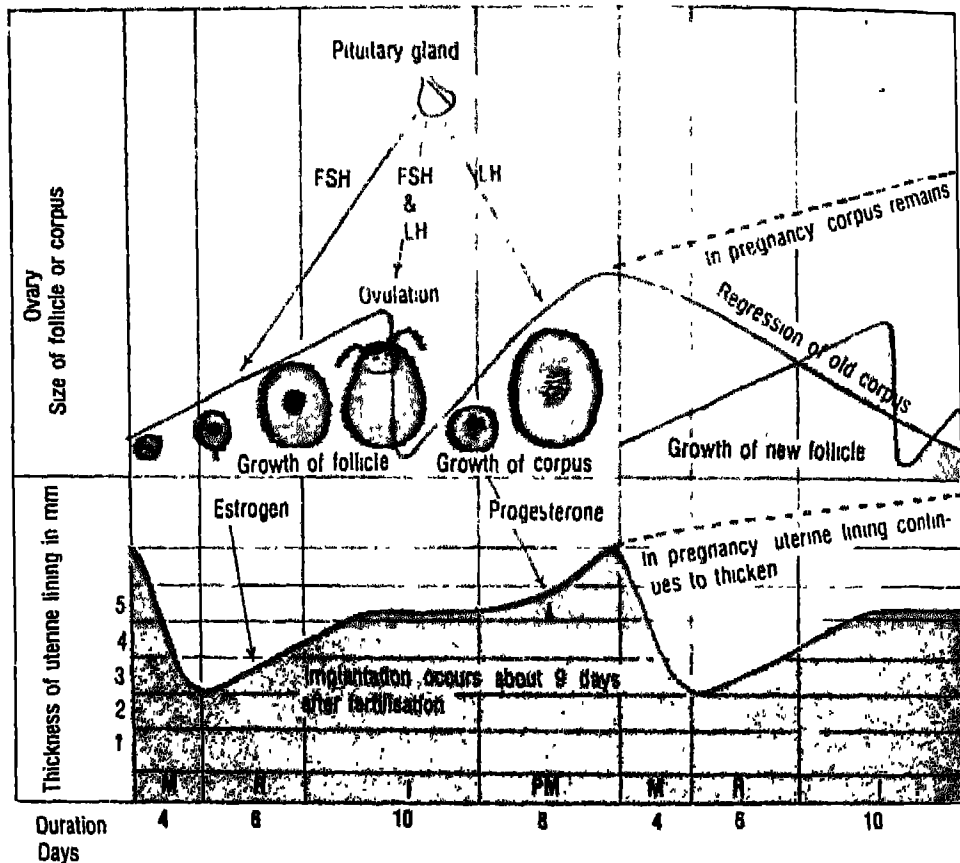


Fig. 40.10 Hormonal control of reproductive function in human female (M = Menstruation; R = Recovery; I = Interval and PM = Premenstrual)

sex organs start their growth changes again. In this way, changes are repeated regularly in a cyclic manner in the female reproductive system. These cyclic changes constitute the menstrual cycle in primate females including women, and the estrous cycle in other mammalian females.

The cyclic changes in the reproductive tract of the primate female extend over

more or less a month (mensem). Unless pregnancy has taken place, these changes end with a discharge of blood carrying broken tissue materials through the vagina. This monthly flow of blood is called **MENSTRUATION**. Hence the name 'menstrual cycle' for the cyclic changes in the reproductive tract of the primate females.

During menstruation, considerable parts of the mucous membrane and glands are broken down and lost from the linings of uterus, Fallopian tubes and vagina. This thins out their mucosae. The uterine blood vessels are also ruptured to cause the bleeding. After menstruation a PROLIFERATIVE PHASE starts with growth and proliferation of tissues on the walls of uterus, Fallopian tubes and vagina. In this phase, in a couple of days, the broken mucous membranes of uterus and Fallopian tubes undergo some repairs such as the formation of a continuous, epithelial lining on the mucous membrane and the repair of ruptured blood vessels in it. Then an ovarian follicle starts growing and maturing into a mature Graafian follicle. An ovum gradually matures in the follicle and estrogens are secreted from the maturing follicle. Estrogens reach the secondary sex organs and stimulate growth and proliferation in their mucosae. The uterine mucosa of endometrium thickens considerably, uterine glands elongate and ultimately become cork-screw-shaped,

contractions of uterine muscles are considerably increased to enhance the uterine movements, the Fallopian tube epithelium gets thickened and its cilia and their movements are increased. While these changes in the Fallopian tubes are intended for conveying the ovum down those tubes, the uterine changes are in preparation for the expected pregnancy (Fig. 40.10). The proliferative phase extends for about 10-12 days and near its end, the ovum is ejected (ovulation) from the Graafian follicle of ovary. The proliferative phase is followed by a SECRETORY PHASE extending over the next 12-14 days. In this phase, the ruptured follicle changes into a corpus luteum in the ovary and progesterone is secreted from that structure. Progesterone produces changes in the secondary sex organs to further the preparations for the anticipated pregnancy. The uterine endometrium thickens further, uterine glands become more cork-screw-shaped and begin secreting a juice in the uterus, and uterine movements are reduced to keep the uterus quiet. All these

#### ESTROUS CYCLE

The estrous cycle consists of cyclic changes in the female reproductive system of non-primate mammals. It differs from the menstrual cycle in two respects. There is no menstruation at the end of an estrous cycle in spite of the breakdown of tissues in the female reproductive tract. Moreover, near the time for ovulation at the middle of the cycle, the high blood titre of estrogens arouses a strong sex urge in the female animal. This state is known as the estrus or 'heat'—the animal receives the male animal only during the short periods of estrus, extending generally over only several hours (e.g. 18 hours in cow) and not during the rest of the cycle. No such specific period of estrus is seen in the menstrual cycle—there the female animal may receive the male at any part of the cycle. Except for these two distinctions the estrous cycle shows events and changes in the female reproductive organs similar to those in the menstrual cycle. The regulation of the estrous cycle is also similar to that of the menstrual cycle—changes in the first half of the estrous cycle are controlled by estrogens and those in the later half by progesterone.

Many animals, both domestic and wild, possess the ability to reproduce in only some parts of the year. The period of the year when an animal may breed, is called its **BREEDING SEASON**, e.g. autumn for sheep, and spring and autumn for bitches. The estrous cycles run only during the breeding season. In many male animals, the testes descend into the scrotum only during the breeding season. The rest of the year is called **NON-BREEDING SEASON**. Throughout the non-breeding season, the estrous cycles remain suspended in the female animal; this suspension of estrous cycles is called the state of **anestrus**.

Many other animals such as cow and buffalo run the estrous cycles all through the years; they are continuously breeding animals and have no specific breeding season.

uterine changes help in the implantation of the fertilised ovum on the uterine wall. Progesterone also inhibits further follicular maturation and ovulation from the ovary in this phase. If the ovum has not been fertilised, the corpus luteum undergoes degeneration in the ovary towards the end of this phase and progesterone secretion declines. The overgrown endometrium cannot be maintained in the uterus and Fallopian tubes. They begin to break down, blood vessels in the uterine endometrium start bleeding and menstruation starts. It extends over the next 4-6 days, to

be followed by the next menstrual cycle.

Estrogens secreted by the Graafian follicle control the changes in the secondary sex organs in the first half of the menstrual cycle. So this half is also called FOLLICULAR PHASE of the cycle. At the beginning of the cycle, the FSH is secreted from the anterior pituitary and stimulates the growth of the Graafian follicle and the secretion of estrogens. When the blood titre of estrogens rises to a peak near the middle of the cycle, their feed-back effect inhibits FSH secretion and stimulates LH secretion. The LH then stimulates ovulation, formation of corpus luteum and progesterone secretion. Changes in the later half of the cycle are controlled by progesterone. So, this half is called LUTEAL PHASE also. Towards the end of this phase, the high blood titre of progesterone causes feed-back inhibition of secretion of the pituitary gonadotropin. The corpus luteum degenerates as a result and progesterone secretion falls. Because of a decline in the blood levels of ovarian hormones, the overgrown tissues cannot be maintained in the uterus and Fallopian tubes; they break down, causing menstruation. With the fall in blood levels of ovarian hormones, FSH secretion starts again and initiates changes for the next follicular phase. In this way, changes in the menstrual cycle are controlled by ovarian hormones whose secretions are ultimately regulated by a cyclic pattern of pituitary gonadotropin secretions.

The menstrual cycle and menstruation remain suspended during pregnancy. They are also permanently discontinued from around 50 years of age; this is called MENOPAUSE. Ability to reproduce is lost in the female after menopause.

## SUMMARY

Animals may reproduce by asexual and sexual modes. During budding, a special kind of asexual reproduction (vegetative) in *Hydra*, a vegetative part of the body enlarges as an outgrowth and gets detached from the parent body to form a new organism. In asexual reproduction by fission, the body of *Hydra* or a flatworm divides into two halves, each forming an independent organism. In sexual reproduction, gametes or sex cells from two animals of different sex unite to produce a zygote whose repeated mitoses form a multicellular embryo. Syngamy is the union of two cells to form a single cell during sexual reproduction. It may be isogamy if both cells are of identical structure, and anisogamy if one cell is a smaller and motile sperm and the other a larger, food laden, non-motile ovum. Sperms and ova are produced by testes and ovaries, respectively. Bisexual animals have both these gonads in the same individual. Unisexual animals belong to two sexes, the male carrying only testes and the female possessing only ovaries.

Parthenogenesis is the development of a full-fledged animal from an ovum without its union with any sperm.

The reproductive system of sexually reproducing animals consists of primary sex organs, viz. testes and ovaries, which produce gametes; secondary sex organs such as prostate and seminal vesicles in the male and uterus and Fallopian tubes in the female, which participate in reproduction but do not form gametes, and accessory sex characters, which distinguish the two sexes in appearance.

The male reproductive system consists of two testes suspended in the pouch of scrotum, a paired duct system consisting of epididymis, vas deferens, ejaculatory duct and male urethra, and secondary sex organs including a prostate, two seminal vesicles, two Cowper's glands and a penis. Testes form sperms and secrete testosterone; prostate, seminal vesicles and Cowper's glands secrete fluids which mix with sperms to form the semen; the duct system conducts the semen to the exterior.

The female reproductive system consists of two ovaries, and a duct system of two Fallopian tubes, an uterus and a vagina. Ovaries produce ova and secrete estrogens and progesterone; the Fallopian tubes conduct the ovum towards the uterus; the uterus lodges the growing foetus and opens to the exterior through the vagina.

Spermatogenesis takes place in the seminiferous tubules of testes. Spermatogonia ( $2n$ ) divide mitotically into primary spermatocytes ( $2n$ ) which divide into secondary spermatocytes ( $n$ ) by meiosis I. Secondary spermatocytes divide into spermatids ( $n$ ) by meiosis II. Spermatids are transformed into spermatozoa ( $n$ ) by spermiogenesis. A human spermatozoon is a long, flagellated motile cell having a head, a middle piece and a tail.

Oogenesis takes place in the Graafian follicles of ovaries. Each primary oocyte ( $2n$ ) divides by meiosis I into secondary oocyte ( $n$ ) and a polar body ( $n$ ). The secondary oocyte divides by meiosis II into an ovum ( $n$ ) and a second polar body ( $n$ ).

The menstrual cycle consists of cyclic changes in the reproductive tracts of primate females, culminating into a menstrual flow of blood from the vagina. It consists of two phases, proliferative and secretory. The first phase follows the preceeding menstruation and consists of growth and proliferation of tissues on the walls of uterus, Fallopian tubes and vagina. In the ovary, a Graafian follicle grows, matures and

secretes estrogens in this phase. The ovum is ejected from the follicle near the end of the proliferative phase. The ruptured follicle subsequently changes into a corpus luteum which secretes progesterone during the secretory phase. In the secretory phase which follows the proliferative phase, the uterine endometrium and glands grow further and the glands secrete a fluid in the uterus. At the end of this phase, the corpus luteum degenerates in the ovary, progesterone secretion fails, the overgrown uterine endometrium breaks down and menstruation takes place. The first half of the cycle is called the follicular phase and the second half is known as the luteal phase because the changes in those phases are controlled by estrogens and progesterone, respectively. The secretions of these hormones occur cyclically because of the cyclic secretions of pituitary gonadotropins in the female. Menstruation results from the fall in the blood levels of both types of ovarian hormones.

## QUESTIONS

- Distinguish between:
  - Asexual reproduction and sexual reproduction.
  - Spermatocytes and oocytes.
  - Graafian follicles and corpus luteum.
  - Fission and budding.
  - Isogamy and anisogamy.
  - Proliferative and secretory phases of menstrual cycle.
  - Primary and secondary sex organs.
  - Male and female reproductive duct systems.
  - Seminiferous tubules and Leydig cells.
  - Spermatogenesis and oogenesis.
  - Vas deferens and vasa efferentia.
- Mark the wrong item in each series:
  - Spermatocyte; polar body; spermatid; spermatogonium.
  - Endometrium; corpus luteum; acrosome; Graafian follicle.
  - Vas deferens; Fallopian tube; epididymis; Cowper's gland.
  - Testes; prostate; seminal vesicles; Cowper's glands.
  - Fallopian tubes; vagina; uterus; ovaries.
- Match the items of Column A with items of Column B:
 

<i>Column A</i>	<i>Column B</i>
(a) Isogamy	(i) Spermatid
(b) Acrosome	(ii) Estrogens
(c) Proliferative phase	(iii) Earthworm
(d) Leydig cells	(iv) Progesterone
(e) Spermiogenesis	(v) spermatozoon
(f) Secretory phase	(vi) Testosterone
(g) Bisexual animal	(vii) Monocystis
(h) Endometrium	(viii) Menopause
	(ix) Uterus



4. Fill in the blanks with correct words:

- (a) Changes in the female secondary sex organs are controlled by \_\_\_\_\_ of the ovary in the proliferative phase of the menstrual cycle while the changes in the secretory phase are controlled by the hormone \_\_\_\_\_.
- (b) Growth of the Graafian follicle is stimulated mainly by \_\_\_\_\_ of the pituitary while ovulation is stimulated mainly by \_\_\_\_\_ of the same gland.
- (c) A primary spermatocyte is produced by \_\_\_\_\_ division while a secondary oocyte results from \_\_\_\_\_ division.
- (d) Uterine glands grow and elongate in the \_\_\_\_\_ phase of the menstrual cycle while they secrete a juice in the \_\_\_\_\_ phase of the cycle.
- (e) Spermatozoa are produced in the \_\_\_\_\_ of testes while ova are formed in the \_\_\_\_\_ of ovaries.
- (f) Corpus luteum secretes \_\_\_\_\_ while Leydig cells secrete \_\_\_\_\_.
- (g) The secretory phase of the menstrual cycle is also called the \_\_\_\_\_ phase because it is controlled by the hormone \_\_\_\_\_.
- (h) Vasa efferentia conduct the sperms out from the \_\_\_\_\_ while vas deferens conducts the sperms from the \_\_\_\_\_.
- (i) A secondary oocyte has a \_\_\_\_\_ chromosome number while a fertilised ovum has a \_\_\_\_\_ chromosome number.

5. Explain the following:

- (a) Failure of testes to descend into the scrotum produces sterility.
- (b) Spermatids possess a haploid chromosome number.
- (c) The first half of the menstrual cycle is called the proliferative phase as well as the follicular phase.
- (d) The second half of the menstrual cycle is called the luteal phase as well as the secretory phase.
- (e) Primary sex organs control the growth, function and maintenance of secondary sex organs.

6. Write briefly the changes in the following organs in the different phases of the menstrual cycle:

- (a) Ovaries, (b) Uterus, (c) Fallopian tubes.

7. Describe the duct system which conducts spermatozoa from the testes to the exterior of the body. Name the hormone controlling the growth and functions of this duct system.

8. Mention the functions of the following:

- (a) Epididymis (b) Fallopian tubes (c) Vagina (d) Uterus (e) Corpus luteum (f) Seminiferous tubules (g) Scrotum (h) Graafian follicle.



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## EMBRYONIC DEVELOPMENT

YOU normally recognise an animal of a particular group only in its adult stage. It is because at this phase of life an animal manifests the characteristic form in appearance, shape and size specific for a group or a species. It also draws your attention by moving and behaving in its own way in the habitat it lives in. But it begins its life quite early as an inconspicuous, tiny, and, very often, non-motile form. All multicellular metazoan animals which reproduce sexually start their life as a single cell. This cell is a product of union of two cells—the male and the female sex cells (gametes). Such a cell is called a zygote, or a fertilised egg or ovum. You have learnt in Chapter 11 in your earlier class how cells divide mitotically or meiotically. The fertilised egg starts development by repeated mitotic divisions which turn it into a ball (sphere) or a disc of a large number of tiny cells. A sphere of cells almost identical in mass and volume to the fertilised egg cell is formed.

You must have seen a heap of bricks on the wayside or in your locality. Perhaps

you have also seen how a skilled mason lays bricks one above the other turning the heap of bricks into a beautiful house of a specific design. The pattern in which bricks are laid decides the characteristic appearance of the house built. Thus you can readily recognise a particular house you once visited for its design and also can distinguish it from others. In animals, the sphere of cells already mentioned may be compared to the heap of bricks. The individual develops from such sphere or disc of cells with characteristic appearance, shape and size. It can also be compared to a house having a specific design, shape and size made of a heap of bricks. However, this is just an analogy. So the spheres of cells we encounter in the development of different animals such as a sea urchin, a frog, a chick or a human being, though initially, they appear to be more or less identical, gradually emerge into individual forms completely different in appearance, shape, size and volume. Indeed, a fertilised egg cell is a specific 'blue-print' for future development.

The story of animal development is a fascinating one. In this chapter you will study the major events in the process of embryonic development (up to the formation of three germ layers) in mammals. The fertilised ovum passes through a series of dynamic changes and identifiable stages. Eventually, through these changing stages it attains an adult organisation often made up of millions and trillions of cells. In totality, the structural changes in a zygote leading to the formation of adult form are called EMBRYONIC DEVELOPMENT. In this dynamic process, you will witness a unique succession of stages in preparation as also the succession of actual stages of development. These are:

- (i) the formation and differentiation of sex cells or gametes (GAMETOGENESIS),
- (ii) the union of male and female gametes (FERTILISATION),
- (iii) the rapid multiplication of the zygote to form cluster of cells (SEGMENTATION or CLEAVAGE or BLASTULATION),
- (iv) the movement and transport of cells in the spherical or discoidal mass of cells already formed (GASTRULATION) to develop a three-layered structure of reoriented cells (GERM LAYERS), and
- (v) the differentiation of cells at different specific locations of germ layers of the developing embryo to form different organs and organ-systems (ORGANOGENESIS or ORGAN FORMATION).

In general, the above stages of development are, to a great extent, similar in diverse groups of higher animals and occur universally in an orderly sequence.

From the account of gametogenesis given in Chapter 40, you can understand well that only 25 per cent of the resultant cells of oogenesis become functional eggs, whereas in spermatogenesis 100 per cent of the total number of cells formed are potentially functional. Let us study in little more details the differentiation, structure and function of sex cells.

### Differentiation of Spermatozoa

Spermatogenesis, the process of differentiation of spermatids into spermatozoa, is an elaborate one. In this process of metamorphosis of a spermatid, the nucleus

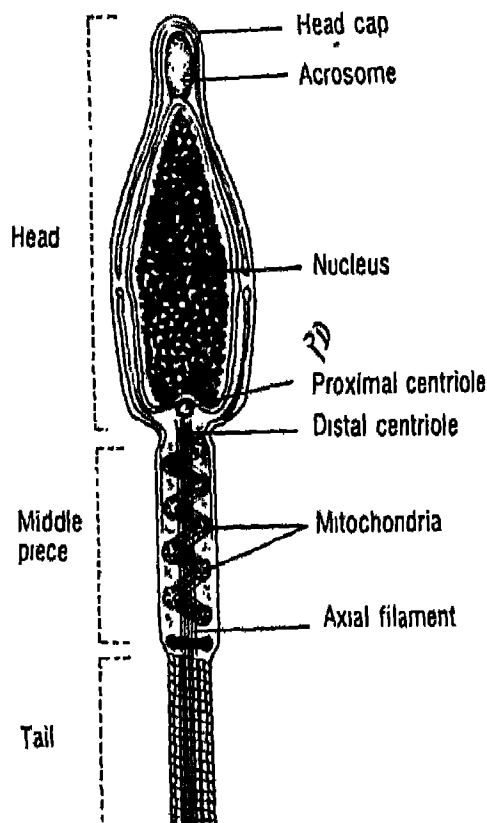


Fig. 41.1 An electron microscopic view of a mammalian sperm (diagrammatic)

becomes exceedingly compact to form the bulk of the sperm head. The centrosomal apparatus of the spermatid undergoes thorough modification to form the motile axial filament of the tail of the sperm. The cytoplasm is reduced extremely in bulk, giving rise to an envelope with a tiny thickened cap, ACROSOME, at the tip of the head of the sperm and a fine investment of the axial filament of its middle piece and tail (Fig. 41.1).

### Structure and Function of Spermatozoa

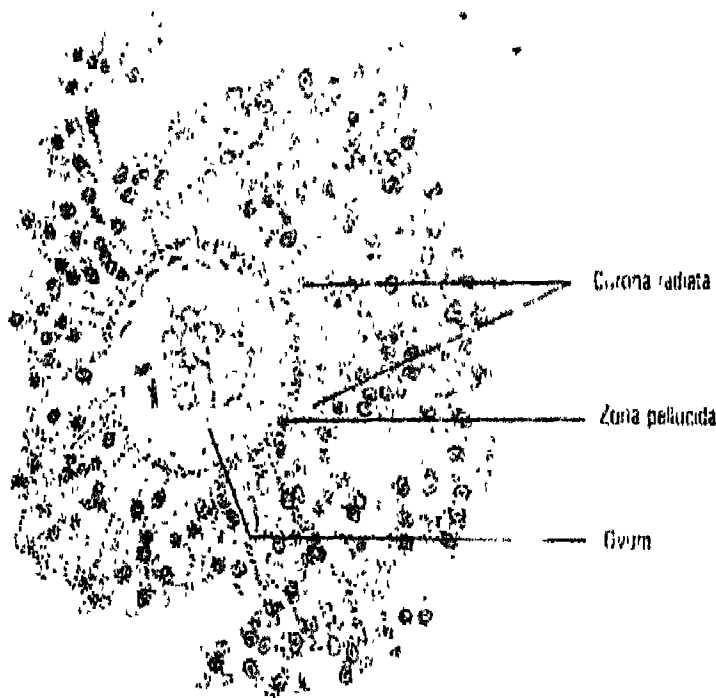
Besides a few exceptions, the basic structure of sperm is the same in all animals. The structural organisation of sperm is such that it provides the sperm the unique power of motility. The typical mammalian sperm, as you know, has four body parts: head, neck, middle piece and tail. Each part is specialised to perform a specific function.

The advent of electron microscope has revealed the finer structures of sperm. The sperm head consists of a large nucleus and an acrosome. The highly compact nucleus contains only concentrated DNA. The acrosome at the tip of the sperm head is a compact mass with a double-layered membrane. This membrane extends down the outer surface of the nucleus to form the head cap of the nucleus (Fig. 41.1). During fertilisation the acrosome facilitates the penetration of the sperm into the ovum by secreting some enzymes. These enzymes dissolve the membrane enveloping the ovum and help the sperm head to enter the ovum. The short neck contains two distinct granules—the proximal and distal centrioles. The proximal centriole plays a crucial role during the first division of the fertilised ovum. The distal one gives attachment to the axial filament of the long tail of the sperm. The

compact mass of mitochondria lodged in the middle piece contains oxidative enzymes to supply energy for metabolism and movement of the sperm. The tail is made up of a central axial filament surrounded by a small amount of cytoplasm and cell membrane as an external sheath. The sperm locomotes by the undulating movement of the tail. Propulsion of the sperm through female ducts and canals needs a liquid medium. The sperms virtually swim in the liquid medium a considerable distance to reach the ovum.

### Differentiation of Ova

In ovary, egg nests are formed by the breaking up of the ovigerous cord. A few cells are always found in the ovigerous cord and nests which are grown larger than the neighbouring oogonial cells. These enlarged cells grow to form primary oocytes. The neighbouring oogonial cells forego the potentiality to become primary oocytes and encircle the growing primary oocyte—the future ovum. These smaller cells surrounding the growing primary oocyte collectively act as protecting and food-purveying investment. In mammals, this cell-cluster (including the future ovum) thus formed is termed PRIMARY OVARIAN (GRAAFIAN) FOLLICLE. Eventually, a fluid-filled cavity is formed inside the follicle. With the increased accumulation of fluid, the follicle enlarges in size and protrudes from the ovary. The enclosed ovum becomes many times larger in dimension in comparison to the enveloping follicle cells. Because of the scanty yolk content, the mammalian ovum is relatively smaller in size with the centrally located nucleus in the cytoplasm. The cell membrane of the ovum becomes considerably thickened. Further differentiation carries the ovum on a slender



mammalian  
ova are  
alecithal.

Fig. 41.2 A human ovum invested by radially arranged follicle cells (corona radiata)

stalk of cells which eventually releases the mature ovum in the follicular fluid. Finally, the mature follicle ruptures and releases the ovum.

### Structure of Ova

Ova are rounded spheres and non-motile. In higher mammals, ova are almost without any yolk (alecithal) with bulky cytoplasm and centrally located nucleus. Ovum is surrounded by a secreted transparent, non-cellular layer, called ZONA PELLUCIDA. Outside this layer there is an investment of radially elongated follicle cells. This cellular investment is called CORONA RADIATA (Fig. 41.2). The cells of corona radiata continue to cling to the ovum for some time after the ovum is

released.

### Fertilisation: Union of Sex Cells

Fertilisation is a dynamic process which results in the fusion of the sperm with an ovum to produce a single diploid cell called zygote. In fact, the sperm contributes only its nucleus. Thus, at the genetic level it brings in the coming together of parental genes—both male and female; hence the hereditary characters. Thus the embryonic life of the individual offspring begins.

Fertilisation performs two basic functions in the process of embryonic development. First, the contact of sperm with an ovum and the subsequent entry of the sperm into the ovum activates the ovum.

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Fertilisation in vertebrates such as amphibians (frogs and toads), reptiles, birds and mammals takes place inside the female's body. So the process is internal. In lower vertebrates like fishes this process is external. In fishes and amphibians the fertilised eggs develop unprotected in water. Among land-dwelling vertebrates, reptiles and birds lay the fertilised eggs covered by the protective shell cover. Development of hard egg-shell is an important adaptation which protects the zygotes and embryos from the dryness of external environment, i.e. the terrestrial environment. The evolutionary uniqueness is witnessed in mammals, where the zygotes and the developing embryos stay in the mothers' uteri being anchored by the extra-embryonic structure, called PLACENTA. Thus in mammals the entire process of development completes inside the mother's body.

This activation is manifested in the ovum completing the second meiotic division and many other changes which lead the fertilised ovum to the next distinct phase of embryonic development, i.e. CLEAVAGE (also called SEGMENTATION). Secondly, it results in the fusion of two haploid nuclei—one from the sperm and the other from the ovum. Thus, diploid condition is restored in the zygote nucleus. The individual develops from the zygote is made up of cells which contain diploid set of chromosomes like its parents.

In the human female, like other mammals, fertilisation takes place inside the

FALLOPIAN TUBE. During coitus semen containing millions of sperms is deposited in the vagina (INSEMINATION). The sperms travel a great distance through the female genital tract beset with chemical hazards in the form of strong acid secretions from the female tract. They also meet with mechanical obstacles while passing through crooked and compressed tract which often gets narrowed or occluded. In an ejaculate of semen, the number of sperms is about 200,000,000. Such a <sup>2x</sup> huge number ensures the reaching of some sperms to the oviduct, the site of fertilisation. Actively motile sperms swim like tadpoles in the fluid medium at the rate of 1.5 to 3 mm per minute to reach the site. Usually, only single sperm penetrates into the ovum. The area of the ovum which extrudes the polar bodies and receives sperm is called the ANIMAL POLE. The pole of the ovum opposite to the animal pole is termed the VEGETAL POLE. The fertilisation process consists of three major steps: (i) penetration of the sperm into the ovum (Fig. 41.3), (ii) activation of the ovum, and (iii) fusion of the sperm and the egg nucleus. After fertilisation the fertilised ovum trickles down to the uterus for implantation.

#### *Chemical and Physical Events of Fertilisation*

In the process of fertilisation, the sperm penetrates the ovum and enters its territory through intricate chemical reaction. The sperm releases chemical substances of enzymatic nature. The SPERM LYSINS is the general name given to these substances. These chemical substances occur in the sperm's acrosome. The sperm lysins dissolve the egg envelopes locally which make the path for the sperm to reach the surface of the ovum. Certain receptors on

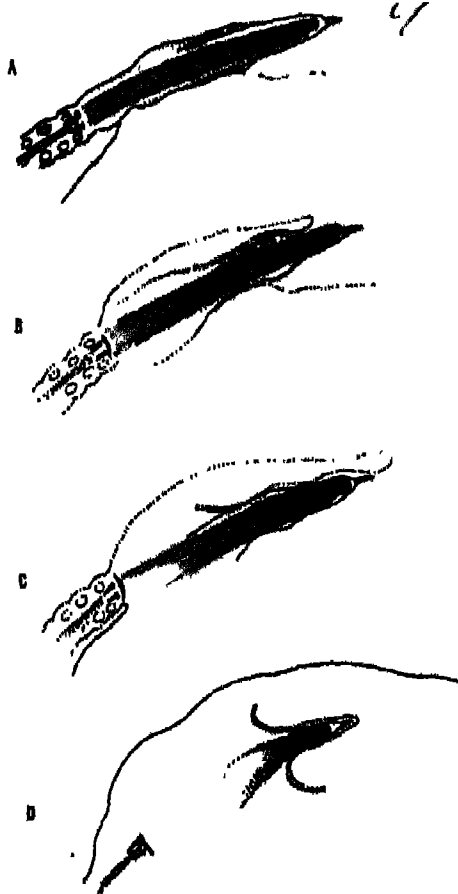


Fig. 41.3 Drawings representing some stages (A to D) of sperm entry in the rabbit egg

the cell surface enable the sperm head to attach with the cell surface of the egg to be fertilised.

You have already learnt about the occurrence of follicle cells (corona radiata) around the egg envelope of a mammalian egg. The ovum extrudes from the ovary and trickles down the Fallopian tube being encircled by the follicle cells. The follicle cells are glued together by the

mucopolysaccharide, an acid called HYALURONIC ACID. The sperm produces an enzyme, HYALURONIDASE (sperm lysin).

The change in a mammalian sperm which prepares it to fertilise the ovum is termed CAPACIATION. As revealed under the electron microscope in this process of capaciation, the membrane surrounding the acrosome breaks and releases its contents, the sperm lysins. With the help of the sperm lysins the sperm penetrates the layer of corona radiata (follicle cells) and zona pellucida. The sperm establishes contact with the surface of the ovum by its lateral surface (Fig. 41.3). This follows dissolution of the plasma membrane of the ovum and the sperm head at the point of contact, and the nucleus and cytoplasmic components of the sperm are drawn inside the ovum (Fig. 41.3).

The entry of the sperm invokes a chemical signal in the egg cell. The signal is transmitted to the egg surface incapacitating hundreds of sperms in the vicinity to enter the egg cell. The rest of the follicle cells around the fertilised ovum persist for some time. However, these cells disperse before the implantation of the fertilised ovum on the inner wall of the uterus.

### From Egg to Embryo

You have just learnt that the fertilisation is a crucial biological process which includes an orderly series of physico-chemical events. It sets the ovum in the path of development of a new multicellular individual. This developmental course is clearly demarcated into distinct dynamic phases. These phases are strictly sequential in nature but may overlap to some extent. Development in mammals follows the same generalised plan and



interrelated sequences as seen in all higher animals including other groups of vertebrates. However, differences are there between mammals and other groups of vertebrates so far as details of developmental mechanisms are concerned. These differences are mainly due to the type of egg cells and the environment in which the development takes place.

### *Cleavage (Segmentation)*

Cleavage is a unique embryological process which transforms the single fertilised egg cell into a sphere of closely aggregated multitude of cells. Immediately after fertilisation the fertilised ovum (egg cell) undergoes a series of cell divisions. The ovum, thus, divides repeatedly in close succession. These divisions are called CLEAVAGE DIVISIONS. The embryos in all higher mammals at an early stage of development start deriving nutrition from the blood in the uterine circulation of mother. As the egg cell contains an extremely small amount of yolk diffusely dispersed in the cytoplasm as the reserved food, so the amount of yolk is absolutely insufficient for the nutrition of the developing embryo. In fact, the quantity as also the nature of distribution of yolk interferes with the cleavage divisions of the ovum in other vertebrates. In mammals, however, due to the presence of insignificant amount of yolk such interference is absent. As a consequence cleavage divisions cut the ovum into complete daughter cells. This type of cleavage (also called SEGMENTATION) in mammalian ova is termed SIMPLE HOLOBLASTIC. Cleavage in the mammalian ovum takes place during its passage through the Fallopian tube to the uterus.

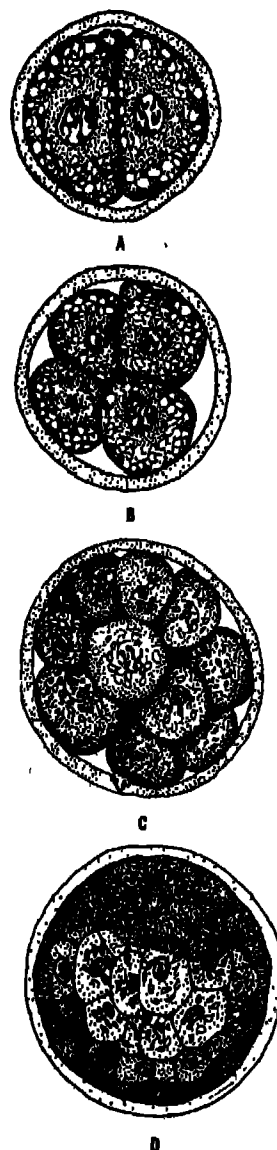


Fig. 41.4 Cleavage in a mammalian ovum (pig) in sectional view  
A. two-cell stage; B. four-cell stage; C. sixteen-cell stage and D. morula stage (diagrammatic)

Formation of Morula Let us now describe the embryonic development in mammals up to the formation of three germ layers. The mitotic spindle of the first cleavage division appears in the cytoplasm of the fertilised ovum at right angle to an imaginary axis which runs through the ovum from animal pole to vegetal pole. The cleavage furrow develops in the cytoplasm of the ovum. The furrow deepens at two poles and eventually divides the ovum into two daughter cells (Fig. 41.4A). The daughter cells are called BLASTOMERES. The plane of this division coincides with the animal-vegetal pole axis. Immediately after the formation of first two blastomeres, which remain adhered to each other, the second cleavage division starts. The second mitotic spindle is formed in each of these two blastomeres. One of these two blastomeres usually divides a little sooner than the other, resulting in a transitory three-cell stage. However, the completion of division of the other blastomere leads to the characteristic four-cell stage (Fig. 41.4B). The second cleavage division occurs at right angle to the first division and to each other. Such a plane of division provides the characteristic four-cell stage—an appearance suggestive of crossed dumbbells. Subsequent cleavage divisions proceed one after another in an orderly manner, but in less precise orientation. Successive cleavage divisions are so rapid that they leave no time to newly formed blastomeres to grow. As a consequence, with more and more segmentation divisions, the resultant blastomeres become smaller and smaller (Fig. 41.4).

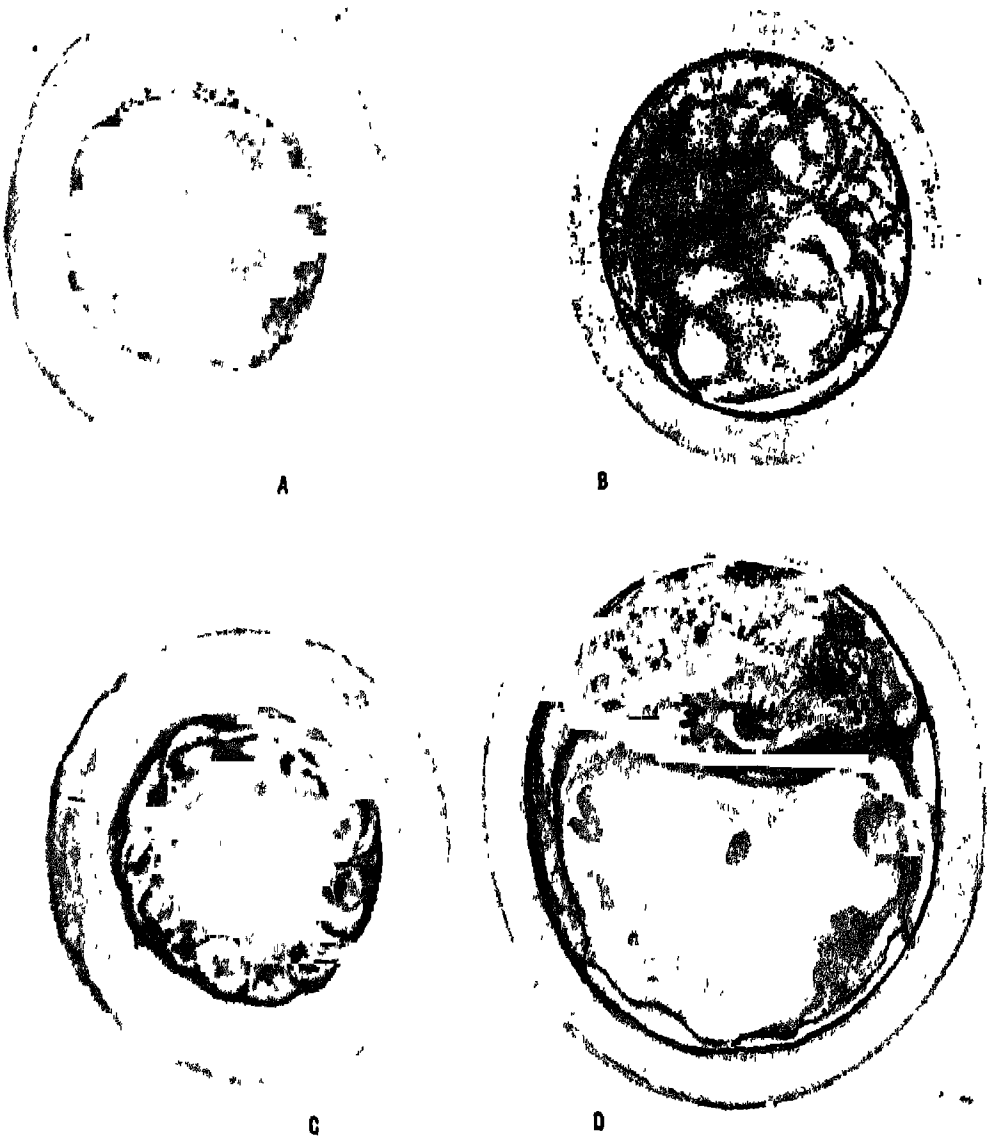
After completion of several segmentation divisions the resultant blastomeres take the shape of a solid ball of cells, which looks like a mulberry. This stage of embryonic development is called MORULA (i.e.

'little mulberry') (Fig. 41.4D). In many mammals, the zona pellucida remains intact throughout the cleavage process forcing the small blastomeres of morula to be housed within the same spheroidal space that was initially occupied by the fertilised ovum. Thus, cleavage divisions do not bring any appreciable increase in the mass of protoplasm of the developing embryo. However, there is a marked increase in the DNA containing chromosomal materials.

#### *Differentiation of Blastodermic Vesicle (Blastula)*

Differentiation of a morula into a blastodermic vesicle (BLASTULA) in a mammal initiates by the dynamic rearrangement of small blastomeres. Due to the rearrangement of blastomeres a central cavity forms inside the morula. Now this sphere of cells with a cavity located at the centre is called BLASTODERMIC VESICLE (blastula) (Fig. 41.5). This newly developed central cavity of blastula is termed BLASTOCOEL (also known as SEGMENTATION CAVITY). As an analogy, if the morula is compared to the solid cricket ball, the blastula can be compared to a hollow tennis ball. At this phase of development, the zona pellucida envelope disintegrates. Disintegration of this envelope facilitates the beginning of rapid growth of the embryo (blastula).

The large sized blastocoel of a mammalian embryo at this phase of development signifies two things. First, from the point of view of the developmental history of different vertebrate groups (i.e. phylogeny) the fluid-filled space (i.e. blastocoel) is the site where the embryos of the ancestors lodged food materials in the form of a mass of yolk. Secondly, from the point of view of the development of the individual



**Fig. 41.5** Transformation of morula into blastodermic vesicle (blastula) in rabbit. A and B. stages of morula; C. initiation of the formation of a central cavity in morula and D, central cavity is more conspicuous and now called blastocoel. Note the prominent zona pellucida around the developing embryo.

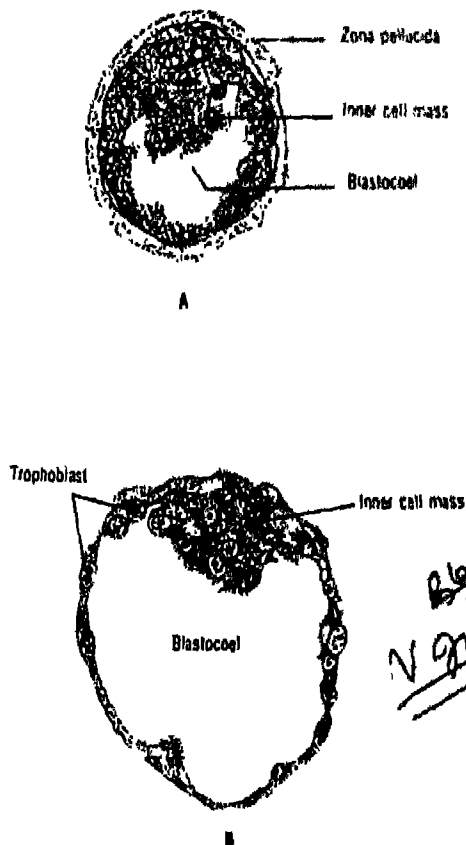


Fig. 41.6 Two stages (A and B) of development of blastodermic vesicle (blastocyst) in pig (diagrammatic sectional view)

embryo (i.e. ontogeny) the blastocoel as yolk space increases in dimension as more and more fluid accumulates within it. This results in expansion of the outer layer of blastodermic vesicle (also called BLASTOCYST) into a voluminous membrane. This membrane at a later stage draws food for the yolkless embryo from the uterine circulation of the mother. Thus the layer

of cells which forms the outer wall of the blastocyst is named TROPHOBLAST or TROPHOECTODERM (*trophos* = to feed).

The cells of the outer wall of the blastodermic vesicle do not enter in the formation of embryo proper. The layer of cells constituting the thin outer wall of the blastodermic vesicle forms protective and trophic membranes. These membranes eventually develop into foetal portion of the placenta (a structure which attaches the embryo with the inner wall of the mother's uterus).

In the process of differentiation of the embryo, an internal cluster of cells aggregate at one pole of the distended blastodermic vesicle (Fig. 41.6A & B). This cluster of cells is called INNER CELL MASS. The inner cell mass is primarily destined to form the body of the developing embryo.

With the completion of differentiation of the blastodermic vesicle within the mother's uterus, the developing embryo gets attached with inner lining of the uterus through the placenta. Next developmental process is the differentiation of three germ layers. Through the characteristic cellular kinetics these germ layers lay the foundation of different organs and organ-systems of the developing embryo.

#### Gastrulation and Formation of Germ Layers

Gastrulation is another visible dynamic event of embryonic development. The cells of the undifferentiated blastula (e.g. in frogs and toads) and the blastodermic vesicle (e.g. in mammals) visibly move in small masses or as sheets of cells to attain the final location. Such movements of cells is called MORPHOGENETIC MOVEMENT and the overall event, GASTRULATION. This process results in the forma-

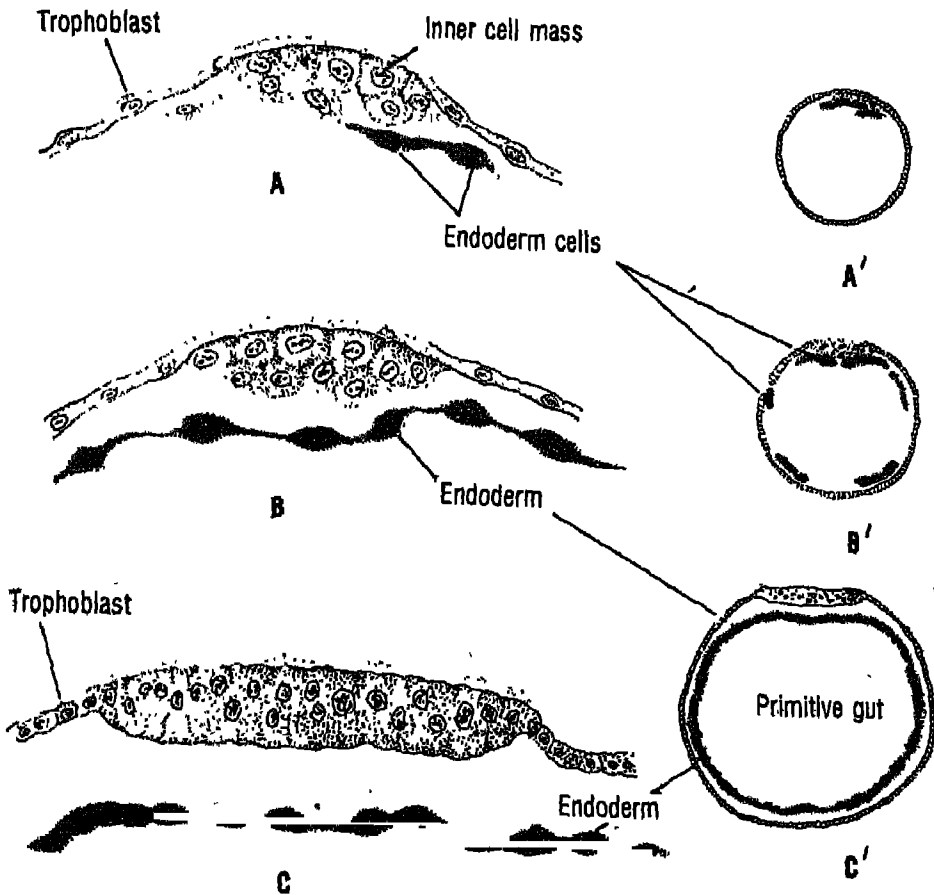


Fig. 41.7 Three stages in the formation of endoderm in a pig blastocyst (blastodermic vesicle) in sectional view (diagrammatic). A—C, partial sections; A'—C'. Sections of the entire embryo

tion of three germ layers.

In all triploblastic animals (i.e. animals having three germ layers in their embryos) including mammals the undifferentiated

cell mass of the young embryo gets differentiated into three germ layers, i.e. ECTO-  
DERM, MESODERM and ENDODERM. Once these germ layers are differentiated, the

developmental fate of the cells composing each of the germ layers gets determined. Thus, each of these germ layers is destined to develop specific organs and organ-systems of the individual to be developed. For example, ectoderm, being the outermost layer of the embryo, differentiates into structures like skin, brain, spinal cord and nerves. Endoderm, which is the innermost layer of the embryo, differentiates into the primitive gut. The primitive gut (also called archenteron; Archi = primitive, enteron = gut), in turn, forms the different structures of digestive and respiratory system, the urinary bladder, the middle part of the ear. Mesoderm, which is the middle layer, differentiates into varieties of other structures like notochord, muscles, heart, blood vessels, kidneys, gonads, etc.

Without entering into the complicated process of differentiation of all these structures (organogenesis), let us learn briefly how the three fundamental germ layers—the cellular basis of differentiation of different organ-systems—are laid.

**Formation of Endoderm:** In mammals the enlargement of the blastodermic vesicle is soon followed by the detachment of some cells from the inner cell mass (Fig. 41.7A & A'). The detached cells push out into the blastocoel to become the first endodermal cells (Fig. 41.7B & B'). These cells rapidly increase in number to constitute the second complete layer inside the original outer layer of the blastodermic vesicle (Fig. 41.7C & C'). Thus, at this stage of development the embryo in a sectional view will look like a tube enclosing another tube of smaller diameter (Fig. 41.7C'). The inner tube with the lumen internally bounded by the endoderm is

called the primitive gut. The primitive gut at a later stage of development differentiates into two portions. One portion within the body of the embryo constitutes the gut tract. The other portion as a distal sac communicates with the gut of the embryo and is termed the yolk sac.

**Formation of Embryonic Disc** Soon after the emigration of the endodermal cells, constituting the wall of yolk sac, the remaining mass of cells of the inner cell mass gets consolidated by regular arrangement of cells. At this stage of differentiation the inner cell mass is called EMBRYONIC DISC (Fig. 41.8A).

**Formation of Mesoderm:** Formation of mesoderm starts only after endoderm is established as a distinct cellular layer. At the caudal margin of the embryonic disc an increased rate of cell proliferation initiates. Such proliferation of cells results in localised increase in the thickness of the disc. The proliferated cells subsequently get detached from the embryonic disc (Fig. 41.8B & C) and form the well demarcated mesodermal layer.

**Formation of Ectoderm:** After the formation of mesoderm, the remaining cells of the embryonic disc arrange themselves in a layer to form the ectoderm (41.8).

#### *Fate of Germ Layers in Embryonic Development*

Prior to the emergence of the germ layers, the multiplication of cells by mitoses is the main developmental event in an embryo. The establishment of the germ layers initiates the phase of differentiation and specialisation.

In fact, even within a particular germ layer, the cells which look alike to the

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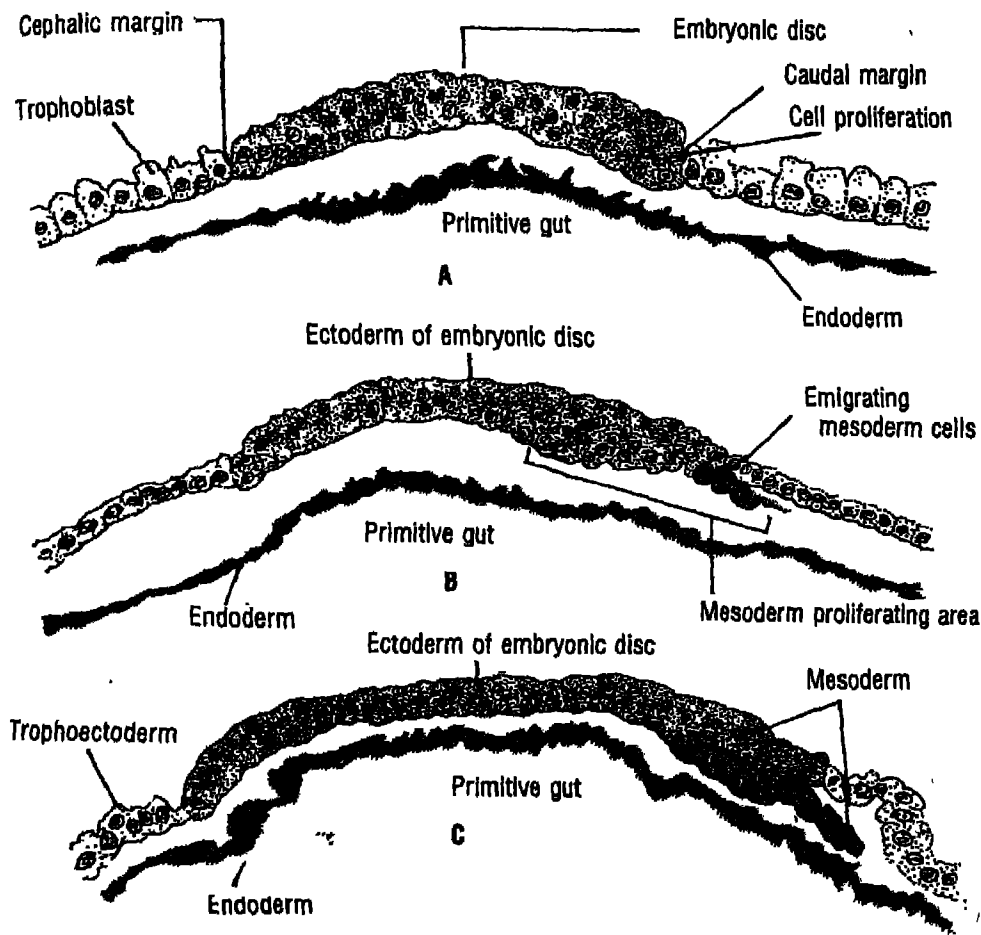


Fig. 41.8 Three stages (A to C) in the formation of mesoderm in a pig embryo (diagrammatic sectional view)

human eye, gradually form the localised groups with different developmental potentialities. These groups of cells change their shape and differentiate into morphologically recognisable structures and organs of the new individual.

As the embryo passes through the process of development, the localised cell groups of the germ layers are sorted out bodily and visibly in an orderly fashion and with unique precision. Depending on the developmental potentialities the

localised cell groups differentiate into specific structures as mentioned earlier. The sorting out of the cells in this process is sometimes attained by folding off from the parent germ layer. Sometimes individual cells migrate from one location to

another and reaggregate. Thus, the structures and organs we are familiar with in adult body gradually take their shape from the primordial cell groups of the germ layers.

## SUMMARY

In sexually reproducing metazoans the embryonic development starts with the fertilisation of an egg cell (ovum) by the sperm. Thus, a fertilised ovum is the product of union of two sex cells—the male and the female gametes. The fertilised egg cell undergoes repeated mitotic divisions which transform it into a sphere or disc of a large number of tiny cells. This sphere of cells is almost identical in mass and volume to the fertilised ovum. In different groups of animals the initial stages of development are more or less identical. Differences in the embryos of diverse groups in their appearance, shape, size and volume emerge gradually. Finally, the resultant adults from these embryos become conspicuously different from each other.

The fertilised ovum in mammals and other higher animals passes through specific stages of development to attain the adult organisation comprising millions of cells. The totality of developmental events which transform a fertilised egg into an adult form is called embryonic development.

The successive preparatory and actual stages of development include: (i) the formation of gametes, (ii) the fusion of male and female gametes, (iii) rapid division of the zygote to form a sphere or disc of cells, (iv) and reorientations of the cells of the sphere or disc resulting in a three-layered structure, and (v) differentiations of cells at different locations of these layers to form structures and organs of the adult organisation.

By the process of spermiogenesis the spermatids differentiate into structurally complex spermatozoa. In mammals, ova differentiate inside the Graafian follicles. Each follicle includes a large, non-motile ovum surrounded by the investment of follicle cells. Ovum is released with the rupture of the mature follicle. Ovum is with bulky cytoplasm and centrally placed nucleus and is almost free of yolk. It has a transparent, non-cellular layer around it.

Fertilisation is the process of union of an ovum with the sperm. In this event the sperm contributes its nucleus and invades the ovum in the path of development. In mammals, fertilisation takes place inside the Fallopian tube. Actively motile sperms swim like tadpoles in the fluid medium to reach the Fallopian tube—the site of fertilisation. Only one sperm gets entry into the ovum. Three major steps of fertilisation are: (i) penetration of the sperm into the ovum, (ii) activation of the ovum, and (iii) fusion of the sperm nucleus and the egg nucleus. After fertilisation, the fertilised ovum trickles down to the uterus for implantation.

Fertilisation is a physico-chemical event. Acrosome in the sperm head releases



enzyme which helps the sperm to penetrate through the follicle cells and the non-cellular layer around the ovum. Certain receptors on the cell surface enable the sperm head to attach with the cell surface of the ovum. Enzymatic dissolution of the cell membranes at the point of contact between the ovum and the sperm head takes place. This facilitates the entry of the sperm nucleus and a portion of cytoplasmic component inside the ovum. The entry of the sperm contents inside the ovum makes the latter impermeable to any other sperms in the vicinity. The follicle cells around the fertilised ovum persist for some time. They disperse before the implantation of the ovum on the inner wall of the uterus.

Cleavage is the process which transforms the fertilised ovum into a sphere of closely aggregated cells. The fertilised ovum divides repeatedly in close succession. The resultant cells are called blastomeres. The plane of the first cleavage division runs through the animal-vegetal pole axis of the mammalian ovum. The first division is followed by the second division of the first two blastomeres. The second cleavage division occurs at right angle to the first division and to each other. This division results in the four-cell stage. Subsequent cleavage divisions proceed one after another in an orderly manner, but in less precise orientation. These divisions occur in great rapidity without any time interval for the growth of newly formed blastomeres. Thus, with more and more segmentation divisions, the resultant blastomeres become smaller and smaller in size. After several such divisions the small blastomeres assume the shape of a compact ball of cells called morula. Cleavage divisions do not bring any appreciable increase in the mass of protoplasm in the developing embryo. But there is a marked increase in the chromosomal DNA contents of its cells.

Due to the rearrangement of blastomeres a central cavity is formed inside the morula. This sphere of cells with a cavity (blastodermic cavity) at the centre is called blastodermic vesicle. With the accumulation of more and more fluid in the blastocoel, the outer layer of the blastodermic vesicle (also called blastocyst) expands into a voluminous membrane. This layer of cells which draw nutrition for the implanted embryo from the mother's uterine circulation is named trophoblast. The trophoctoderm does not form part of the embryo proper and eventually develops into the foetal portion of the placenta.

An internal cluster of cells, called 'inner cell mass' aggregates at one pole of the distended blastodermic vesicle. the 'inner cell mass' forms the body of the embryo proper. The blastodermic vesicle, as the developing embryo, gets implanted in the inner wall of the mother's uterus with the help of the placenta.

Gastrulation is the visible dynamic event of cell movements (morphogenetic movements) in the blastodermic vesicle. The cells of the blastula or the blastodermic vesicle move in small masses or in sheets to reach the final locations. The cells of the blastula (blastodermic vesicle) thus get differentiated into three germ layers — ectoderm (outer), mesoderm (middle) and endoderm (inner). Each of the three germ layers is destined to develop specific organs and organ-systems of the developing animal.

Endoderm in a mammalian embryo is formed as the second layer by the delamination of cells from the 'inner cell mass'. With the formation of inner endodermal layer the embryo, in a sectional view, appears like a tube enclosing another tube of a smaller diameter. The inner tube with the lumen internally bounded by the endodermal cells is called primitive gut.

Soon after the constitution of the wall of the yolk sac, the remaining

cells of the 'inner cell mass' get consolidated by regular arrangement. At this point of differentiation the 'inner cell mass' is called embryonic disc.

Formation of mesoderm initiates only after the formation of endoderm as a distinct cell layer. At the caudal margin of the embryonic disc, the increased rate of cell proliferation results in the localised thickening of the disc. These proliferated cells subsequently detach from the embryonic disc to establish as the well-demarcated mesoderm.

After the emergence of the mesodermal layer, the rest of the cells of the embryonic disc orient themselves in a layer to form ectoderm.

The establishment of germ layers starts the phase of differentiation and specialisation. The localised cell groups of the germ layers are sorted out in an orderly fashion and unique precision. Thus, the structures and organs of the animal body gradually take their characteristic shapes.

## QUESTIONS

1. Enlist the major phases of embryonic development.
2. Distinguish between :
  - (a) spermatogenesis and spermiogenesis,
  - (b) corona radiata and zona pellucida.
3. Draw a mammalian sperm and label its four major parts.
4. Compare the structure of mature mammalian sperm and ovum.
5. Write three essential points about the mechanism of fertilisation.
6. 'Fertilisation is a physico-chemical process'. Explain.
7. What are the significant differences in the mitotic divisions in the process of morula formation and gamete formation?
8. Describe the formation of blastodermic vesicle in a mammalian embryo.
9. Distinguish between:
  - (a) morula and blastula.
  - (b) blastulation and gastrulation.
  - (c) trophoectoderm and ectoderm.
10. Describe the formation of three germ layers in a mammalian embryo.
11. What are the main structures and organs which differentiate from the ectoderm and endoderm of an embryo?
12. 'A fertilised egg is a blueprint of future development'. Explain.

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## GROWTH, REPAIR, REGENERATION, AGEING, DEATH

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IN the pervious chapter you have studied how a fertilised egg of a multicellular animal is transformed into an embryo. You must have noticed the unique orderliness in this developmental process. Though apparently it seems that the event of development ends with the formation of different organs and systems in the embryo, transforming it into a young individual (that is, a foetus in the case of a mammal), it does not. In fact, it continues in some form or other almost throughout the entire span of life. Change is the key word of development and differentiation which operates till the death of the individual animal. An embryo is transformed into a young one through a series of changes. It grows through a set pattern to become a full-grown one (GROWTH). That is, it attains a final shape, size and weight (excluding the weight of food in its alimentary canal). It performs all the vital life processes to remain alive. In the body of multicellular animal, cells and tissues meet with constant wear-and-tear process

spontaneously and sometimes accidentally. Some of these cells and tissues, and sometimes even the body parts of some animals, are replaced and renewed (REPAIR and REGENERATION). You have learnt in Chapter 2 that the members of animal species live through an average period of time (life-span), which varies from species to species. They gradually show signs and symptoms of growing old (AGEING) and, eventually, die.

All the above changes (other than the death) may be described as post-embryonic developmental events at the level of an individual. At the cellular level, these changes involve one, two or more of the processes of growth, division, movement, elongation, differentiation, ageing and replacement of cells. Now you will study briefly the processes of growth, repair and regeneration, ageing and death.

### GROWTH

You must have seen kittens growing into cats, puppies into dogs and human babies

into young children. Have you ever wondered how they attain such a change? This is because of the biological process of growth. Growth is an important property of life. All living objects exhibit growth. You have learnt about plant growth in chapter 31. Let us now try to understand the biological meaning of growth and try to comprehend its nature and process in animals.

The body of all multicellular animals is a co-operative of cell aggregates differentiated into tissues and organs. So outwardly perceptible changes in shape and increase in size, volume and weight involve some concurrent changes in the cells the animal body is made of. A fully formed animal embryo is constituted of all or most of the organ rudiments. Thus, at this stage, the morphological plan of the animal body is established. All the early developmental stages described in the preceding chapter may be collectively called PREFUNCTIONAL STATE OF DEVELOPMENT. The biological processes of growth and differentiation enable the animal to enter the FUNCTIONAL STATE OF LIFE.

Growth may be simply defined as the 'increase in size and weight of the organism due to the synthesis of new protoplasm (also the fibres and connective tissues or matrix which are formed by the cells of higher animals like a mammal as apoplasmatic substances)'. You have already learnt about the building up or anabolic and breaking down or catabolic process of metabolism. So the growth of human or any other higher animal body takes place by the addition of new substances, both protoplasmic and apoplasmatic, when the anabolic process dominates the metabolic activity. Conversely, when decomposition exceeds synthesis, first the internal food reserve (fat in

the adipose tissues) is consumed to run the body machine, and then the energy is obtained at the expense of proteins of the protoplasm. This causes the depletion of the living matter, resulting in DEGROWTH.

By now you have learnt that the visually perceptible growth of the individual animal and the intrinsic growth at the cellular (protoplasmic) level are just the two sides of the same coin. Let us now explain these two aspects of growth.

### Cell Reproduction and Cell Growth

At the cellular level, the growth of all multicellular organisms is governed by two main activities. These are reproduction and growth of individual cells of the body. You have already studied under the section on cell cycle and mitosis in Chapter 11, how with unique precision the cells divide following the cycle of phases G<sub>1</sub>, S, G<sub>2</sub>. During the interphase stage, new materials such as nucleic acids and proteins are synthesised in the cells and thus the cells grow.

The growth of individual cells composing the body is the vital and the most essential factor of growth in all multicellular animals. The rhythmicity of cell multiplication and growth can be studied well in tissue culture or in culture of unicellular organisms. But it is extremely difficult to measure the actual growth of tissue cells within the body because of their size and location.

### Growth of the Animal Body

By now you have understood that the growth of an animal is related to the growth of the body cells. But the relationship between the two is by no means a simple one. In tissue culture with suitable nutritive medium tissue cells may grow

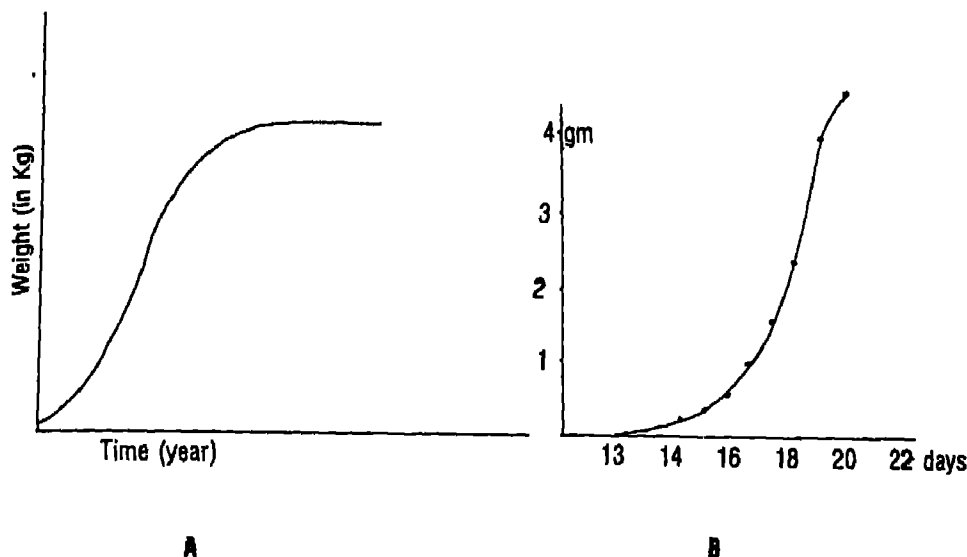


Fig. 42.1 A. Ideal sigmoid curve; B. Sigmoid curve depicting intrauterine growth of the white rat

exponentially like the unicellular organisms. But in tissue cells inside the body of multicellular animals altogether different conditions exist and, thus, they do not grow exponentially.

The growth of multicellular animals in relation to growth and multiplication of their body cells falls under three categories.

In the first category, the volume of the body increases due to the growth of body cells without any increase in the number of cells. Rare examples of such growth are found in Aematoles, rotifers and a group of early chordates (tunicates). This type of growth is called AUXETIC GROWTH.

In the second category, growth results

due to the rise in the number of cells constituting the body. The increase in the number of cells is brought about by the mitotic divisions. In this case, however, the average size of the cells remains the same or increases almost insignificantly. This type of growth is witnessed quite commonly in embryos (See Chapter 41). It is also the characteristic of prenatal growth of higher vertebrates. This category of growth is described as MULTIPLICATIVE GROWTH.

Post-embryonic growth of animals in general is due to mitotic multiplication of some special types of cells occurring in specific locations of the body. The differentiated cells of organs and tissues of the

body lose the capacity of division. As you know, they perform physiological functions for the survival of the animal, whereas the special cells remain in undifferentiated state as reserve cells. In case of necessity, they reinforce and replace the worn-out differentiated cells. In such an event they differentiate into the type of cells that they reinforce and replace. This type of growth constitutes the third category and is called ACCRETIONARY GROWTH.

#### Animal Growth Rate

As discussed earlier, by growth we mean the perceptible and measurable increase in the mass of living substance. So by simply weighing a growing animal if you find an increase in weight you can infer that growth has occurred. All higher animals,

including man, grow at a specific rate and rhythm. They normally stop growing long before the death (if the total body mass of the individual is considered). The growth rate is not uniform, rather it is differential. That is: they grow at different rates at different periods of life. The rate of growth can be depicted in a curve by plotting the weights of the individual taken at different time intervals (in years) on a graph paper.

*Growth Curve:* By weighing a growing animal, say a puppy or a human baby, from birth till the growth ceases (adulthood) and plotting the weights (in kg) against time (in years) on a diagram one can easily get a growth curve (Fig. 42.1A). When the data (weights) are plotted against time, the curve will rise slowly at first showing a slow increase in the weight of the body

HOW THE WEIGHTS OF DIFFERENT PARTS OF HUMAN BODY  
CHANGE FROM BIRTH TO ADULTHOOD

Part of body	Weight (kg)	
	Newborn baby	Adult male
Muscles	0.8	30
Skeleton	0.4	10
Fat	0.8	10
Brain	0.4	1
Rest of the Body	0.9	19
	3.3	70

Note: All the above figures are approximate. They vary from individual to individual. Adult females, too, tend to weigh less than most males, have less weight of muscle and skeleton and more fat.

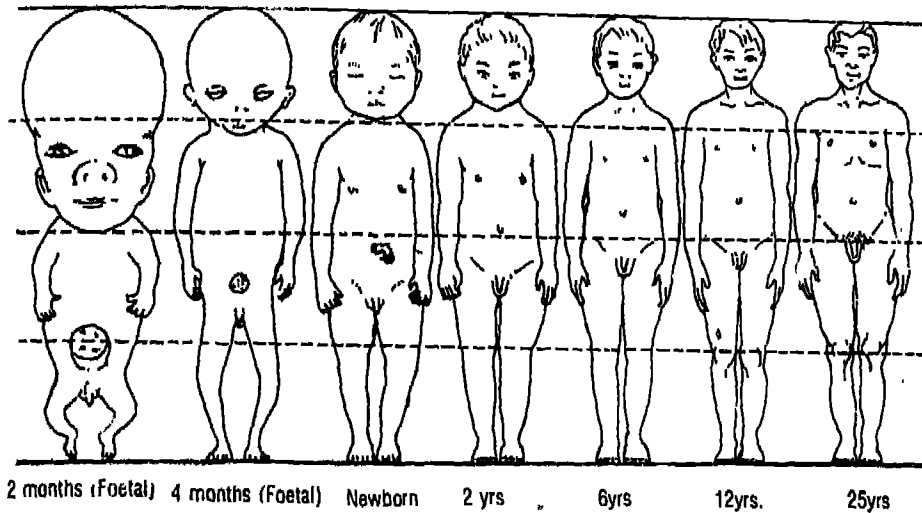


Fig. 42.2 Foetal and postnatal stages of a human being drawn to the same total height to show the characteristic age changes in the proportions of different body parts

(or size), more precisely the living mass of the body. Then, there will be a steep rise of the curve for a period and in the last part the rise of the curve will gradually slow down and run parallel to the horizontal base line indicating time (Fig. 42.1A). Such a curve will usually be S-shaped and is called SIGMOID CURVE. This is the characteristic growth curve of all higher animals including man. If the increments in growth for equal time intervals are measured, the increments during different time-periods of life of an individual animal can be estimated. The difference between the initial and the final weight (or size) of an individual, for any period of time (irrespective of other factors) is the **ABSOLUTE INCREASE**.

#### *Growth of Human Body Parts*

In human beings, as in other animals, the

growth of different body parts (head, neck, thorax, limbs, endoskeleton and internal organs) does not occur uniformly at the same rate till they attain the final shape, size and weight. The growth rates of different body parts are different. If you examine a human baby critically from birth for years you will be amazed to note how shape, size and weight of the body as a whole changes at different rates and paces (Fig. 42.2).

For example, a human foetus or a new born human baby has a head disproportionately larger than the rest of its body (Fig. 42.2). You will get a clear idea of growth (external appearance, shapes and sizes of morphological parts of the body) of an individual by comparing his photographs taken at birth, during

early and late childhood, and during adolescence and adulthood.

#### *Hormonal Control of Growth Rate in Man*

The rate of growth in man from birth to 10-13 years of age (childhood) is quite slow. Thymosin hormone secreted from the thymus gland controls the growth during this age period. Towards the end of childhood due to the enhanced activity of thyroxine and somatotrophic hormones (STH) growth rate starts increasing. During puberty (14 to 18 years of age) the rate of growth becomes fast and reaches the peak point due to the enhanced secretory activity of pituitary and other endocrine glands. At this phase of life due to the action of testosterone in males and oestrogen and progesterone in females the secondary sexual characters appear in the body. With the completion of the puberty stage the human male and female become

full grown. Sex organs in both the sexes attain full maturity. Usually after 18 years of age the physical growth of the body starts declining and almost ceases after the age of 22-23 years.

#### APPROXIMATE AGES OF SEXUAL MATURITY IN SOME COMMON SPECIES OF MAMMALS

Species	Age of Maturity
Human being	11-16 years
Asiatic elephant	8-16 years
White-handed gibbon	8 years
Fin whale	3 years
Rhesus monkey	2-4 years
Horse	1 year
Cat	6-15 months
Dog	6-8 months
House mouse	35 days

Fig. 42.3 depicts the X-ray diagrams of the phalanges and small pieces of bones of palm and wrist of a human child at the age of 5 years (A) and 10 years (B). Note the gaps between phalanges and the small pieces of bones due to their cartilaginous nature in A. Due to the calcification and growth of small pieces of bones gaps have been minimised in B. The growth of the body also results in the elongation of bones

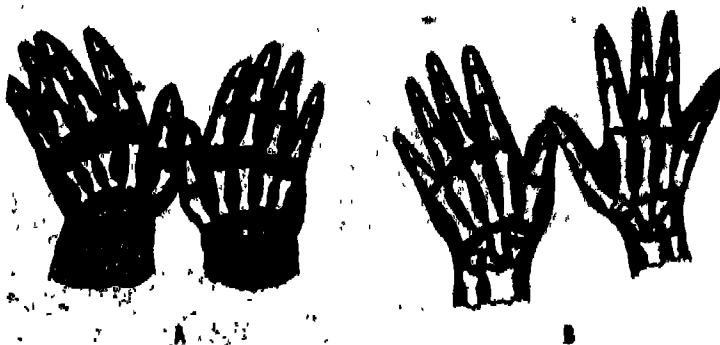


Fig. 42.3



### REPAIR AND REGENERATION

Our body spontaneously loses cells from some specific organs. From the surface layer of the skin and the inner lining layer of the gut, cells are regularly peeled off and replaced by the newly formed cells. Red blood cells live for a short span of life and die inside the spleen. Red blood mother cells in the bone marrow regularly generate new cells to replace the dead cells. Such spontaneous loss of cells and regeneration is common in vertebrate and invertebrate animals. So hosts of animals in their adult and larval life enjoy the power of cell replacement and regeneration. Man and other animals receive cuts and wounds which are soon healed up by localised cell proliferation and migration. A large variety of animals can restore the accidentally or spontaneously damaged or severed body parts, structures or organs. The restoration takes place due to the temporary awakening of the morphogenetic process in the body. This process includes cell multiplication and differentiation (in some cases dedifferentiation). Such post-embryonic developmental events in multicellular animals are collectively called repair and regeneration. The climax of this process is the regeneration of the whole body from each of the several body fragments in Hydra.

Regeneration, a morphogenetic mechanism, can be described as a 'process of repair, replacement or revival of the damaged and severed body parts (structures) or reconstruction of the whole body from a small fragment of it during the post-embryonic life of a multicellular animal'.

In fact, most of the multicellular animals have the ability, at least to some extent, to reconstitute the lost or damaged body parts. The power of regeneration

varies widely in different types and groups of animals. Some can reconstitute a small body part and others a large one. While some forms can restore the whole body from a small fragment, others fail to do that. A few types such as Hydra and Planaria are endowed with the power of reparative regeneration of a part or parts of the body. Let us now have a brief overview of this post-embryonic morphogenetic process in different groups of animals.

### Regenerative Ability in Different Animals

REPARATIVE and RESTORATIVE REGENERATIONS are the two principal categories of animal regeneration. While restorative regeneration is quite common in some invertebrate groups, the reparative one is a common phenomenon in both invertebrates and vertebrates.

Earthworms and allied annelids are capable of regenerating a few body segments severed from either or both the ends (anterior or posterior) of the body. Molluscs are able to reconstitute the damaged eyes, eye-stalks, parts of head and foot. Limbs are regenerated in some insects, crustaceans and spiders. Starfish and other echinoderms are well known for fast regeneration of their broken arms.

Among amphibians, salamanders and axolotl larvae are unique for their power of regenerating some organs and body parts such as limbs, tail, external gills, jaws, intestine and eye structures throughout life. Tadpole larvae (of toads and frogs) are capable of regenerating the amputated tail as also the hind legs when quite young. Regeneration of some parts of fins in fishes, the tail in lizards and the beak in birds is a familiar occurrence. Mammals, including man, are incapable

### AUTOTOMY

Some animals escape danger by sacrificing a body part. On being threatened the leg in some crabs or the tail in some lizards breaks off. Echinoderm throw off their internal viscera whenever threatened by a predator. This phenomenon of self mutilation of body is called AUTOTOMY. The lost parts (tail, limb, viscera) are restored by the process of regeneration. Autotomy is perhaps a special adaptation for escaping the dangers such as an attack by a predator.

body parts. However, the liver as an exception, has the extensive power of reparative regeneration. If a part of the liver is surgically removed the cells of the remaining part undergo repeated divisions until the original volume of this vital internal organ is restored.

### Mechanisms of Regeneration

Two primary mechanisms of regeneration in animals were recognised first by T.H. Morgan. One of the two is MORPHOALLAXIS which involves the reconstitution of the whole body (all missing structures and parts) from each of the small fragments by reorienting and reorganising the existing body cells. As a consequence, the regenerated organism becomes conspicuously

of restorative regeneration of external

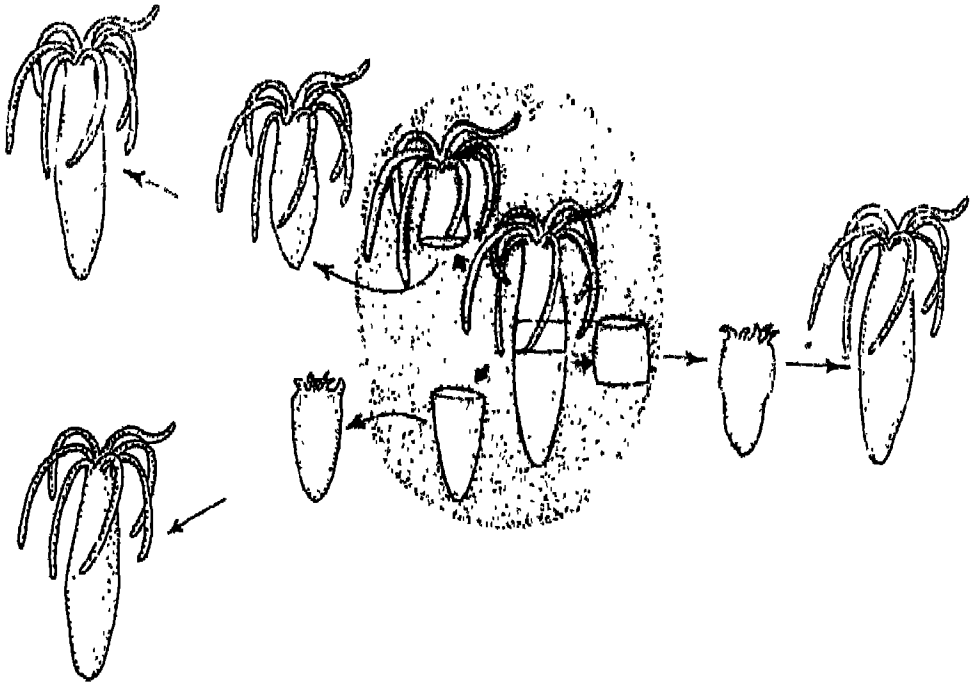


Fig. 42.4 A. Regeneration in *Hydra*. Each of the three body segments regenerates into a fully formed individual.

smaller than the original one (e.g. Hydra) ever, it grows and attains normal size after the completion of the process (How- sometime). The other mechanism is



**Fig. 42.4 B** Cellular architecture of the hypostome regeneration in *Hydra* (anterior part in a longitudinal section) (Photomicrograph under the oil immersion objective lens of a light microscope). Note the regenerating dome-shaped hypostome at the cut end (top). The distinct ectoderm and the endoderm separated by a thin layer of mesoglea (revealed as thick black line) are also visible in the body wall ( Courtesy: Prof. J. Mitra).

EPIMORPHOSIS which takes place by the proliferation of the new tissue cells from the surface of the wound. Regeneration of limb, tail, etc. (e.g. salamander, lizard) occurs by the process of epimorphosis.

A few groups of animals such as porifers (sponges), coelenterates, flat worms, nemerteans and some ascidians have the ability to reconstitute the whole body of the organism from a small, isolated portion or fragment of the original body. The *Hydra* among coelenterates and the *Planaria* among flat worms exhibit this type of regeneration. When their body is cut into a few to several parts (Figs. 42.4A and 42.5) transversely, each part

regenerates into a small complete individual. The *Hydra* has the unique faculty of regenerating the decapitated oral (hypostomal) end again and again. Such power of repetitive regeneration has bestowed upon this small animal the quality of virtual immortality. Fragmentation and regeneration are the familiar mode of asexual multiplication of body in several of these animals.

Regeneration of a lost limb in salamander involves first the spreading of epidermis from the edges of the wound to cover the exposed surface. This process takes one or two days. During the next few days the epidermis covering the wound starts

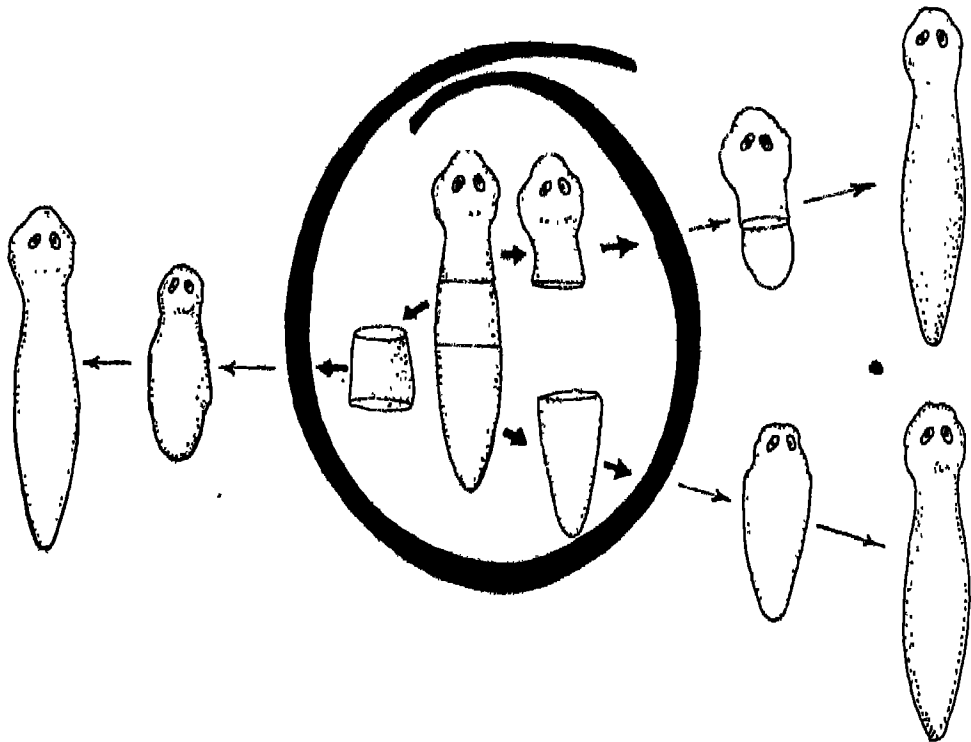


Fig. 42.5 Regeneration in *Planaria*. Each of the three transversely cut body fragments regenerates into a fully formed organism.

#### RECONSTITUTION OF THE BODY FROM ISOLATED CELLS

Sponges can be easily dissociated into their body cells. Isolated cells crawl along the surface of the container reaggregating themselves into large masses. Such aggregates reorganise into new individuals. Different types of isolated body cells (i.e. archaeocytes, collar cells and dermal cells) reaggregate to restore the body organisation. These cell types sort them out and take up their specific positions in restored organisation. Each type of cells performs the same function as it performed in the original sponge body. Similarly, the individual *Hydra* can also be dissociated into free cells. Such cells can also aggregate and restore the body organisation with clearly demarcated ectoderm and endoderm.

bulging outward and takes a conical shape. A mass of accumulated cells below the epidermis proliferates actively and together with the epidermal covering forms the REGENERATION BLASTEMA OR BUD. This bud then undergoes differentiation to restore the internal and external structures of the lost fore-or hind-limb and eventually the rudimentary limb is formed. Regeneration in a functional adult or larval body in almost all cases is influenced and controlled by the neural and hormonal factors.

From the foregoing account, you may like to conclude that some animal groups which are lower in the scale of evolution with simple organisation, have greater

power of restorative regeneration than the higher ones with complex organisation. In higher groups of animals this power is limited to reparative regeneration only.

#### AGEING

You know all living organisms live through a span of time and then die. The average life-span of different groups of animals varies widely (see Chapter 2). Some live for a short period and some for an intermediate period, while some others live for several years or decades and even centuries. It is believed that *Hydra* as an exception, is an immortal creature being not subject to ageing. Every animal grows, attains maturity and then becomes old and senile. Death comes as the end result of old age. So the animal lives through a normal span of life. However, the average life-span of living organisms does not take into account the premature death due to accidents and predations. Once the physical maturity is attained further changes take place as the body ages.

With the advancement of age after maturity the body of an individual undergoes certain gradual changes. These are:

- (i) decline in the metabolic efficiency.
  - (ii) decrease in the power of replacing the worn out cells, repairing the damaged tissues, organs and organ-systems.
- One or more vital organs of the body (e.g. heart, kidneys, brain, liver, etc.) becomes functionally inefficient.

Manifestation of these changes as the individual grows older is known as ageing. Such ageing ultimately results in death of the individual. Thus, ageing may be defined as the deterioration in the structure and function of the body cells, tissues and organs of an animal.

## Changes with Age

### 1. Morphological and Physiological Changes

You may be familiar with some visible changes due to ageing. You must have noticed old men and women with thin, shrivelled and stooping body and with dry wrinkled skin. These are conspicuous visible changes. Signs and symptoms of ageing in man are too many. Some are externally observable, while others relate to structure and function of internal organs and systems. Let us now discuss some of these signs and symptoms.

With age, the efficiency of the heart to pump blood drops. The brain and the kidneys receive far less blood; the amount of blood circulating through the lungs decreases. With the advancement of age, the kidney tubules and the taste buds in the tongue are reduced considerably in number. The bone marrow produces far less red blood cells. Cells gradually lose the capacity of retaining water; tissues become drier; the volume of blood in the body decreases. All these changes in old age result in reduced circulation of blood and decreased formation of urine. The old man is characterised by thin, shrivelled and stooping body with dry and wrinkled skin, flabby and emaciated weak muscles and brittle bones. Such changes also occur in other mammals and other higher animals.

You are already aware of externally manifested signs and symptoms of ageing. These can be easily studied and found out. All these changes are, in fact, the result of physical and physiological changes within the cells and intercellular spaces in the tissues. The cellular and extracellular changes cannot be easily investigated.

The branch of biology named GERONTOLOGY deals with the study of the process of ageing. Gerontologists have worked

out quite a large number of changes in cells and extracellular substances of different tissues of several kinds of ageing animals.

### 2. Cellular Changes

Chromosomal abnormalities and gene mutations in the nuclei of body cells are the conspicuous changes occurring due to ageing. Thus, such changes alter the genetic material—the DNA structure. For example, in mice, dog and man with the increase in age, the liver cells exhibit increased number of chromoso-

#### AGEING—SOME INTERESTING FACTS

- Ageing causes considerable cell deaths in nerve tissues. Dead cells are not replaced by the newly formed ones, as the cell divisions in nerve tissues cease quite early in life. On an average, 20 per cent of nerve cells in the brain die at the age of seventy. It often affects memory, especially of recent events.
- Power of hearing starts becoming less acute after the age of ten.
- Egg production and menstruation ceases about 30-40 years after the first one. This change due to ageing is called 'menopause'.
- Rapid coordination of body parts starts declining after twenties.
- Average life-span of women is longer than that of men. The biological process of ageing is faster in human males than in human females.

mal aberrations. It has been found that with increasing age, the enzyme ALDOLASE synthesised by the mice liver cells becomes more and more inactive. The body cells of older animals contain greater amount of defective proteins. This is due to the increased defects in the DNA structure. Pigment accumulation in the cells of the aged animals increases considerably, especially in the tissues of the brain and muscles which lose the power of division quite early in life. Some experts believe that these pigments are the worn-out cell-organelles such as mitochondria.

With the advancing age, the body cells gradually lose the power of multiplication. Cells from the lungs of a human foetus in a tissue culture medium keep on dividing for about 50 times and then their vitality ceases and they die. On the other hand, the lung cells obtained from the aged human being divide far less number of times. The power of multiplication of cells in different tissues of the body is different. Further, it seems that the cells of different tissues exhibit age-related changes (changes that characterise ageing) at different rates.

### 3. Extracellular Changes

Cells secrete various substances which fill the intercellular spaces in all tissues. These substances include polysaccharides and fibrous proteins. Roughly, 40 per cent of the total protein content of the body comprises collagen. Age-related change in collagen has been extensively studied. As the animals grow older the properties of collagen undergo marked changes. These changes are directly linked with the process of the ageing of the cells and the body as a whole.

Collagens, one of the important extra-

cellular protein, when young are permeable, flexible and easily soluble. Ageing makes collagen less permeable, rigid and insoluble. Such alterations in the properties of collagens interfere with the functions of cells that they surround. Oxygen and nutrients find it difficult to diffuse into the cells. Changes in the properties of the surrounding collagens stand as a definite impediment for the smooth expulsion of carbon dioxide and nitrogenous wastes from the cells of the tissues. Thus, the old and aged collagens as extracellular substance obstruct the diffusion of materials into and out of the cells. Such mechanical obstructions result in the deterioration of cell functions and hasten the ageing process of the cells composing different tissues including those of the vital organs.

### Ageing—Some Unanswered Questions

Till today, the biological process of ageing is not fully understood. Why do animals undergo ageing? Why do some groups of animals age earlier and have shorter life-span than others? Why do even the individuals of the same group not age at the same rate and time? Why even within the body of an individual do different types of cells and tissues show the signs and symptoms of ageing at different rates and times? Why do different cells, tissues and organs of animals deteriorate in structure and function as they grow older? What are the causal reasons behind all these events and differences? What are the factors primarily responsible for all these? Investigators are still continuing their search to find answers to these questions. Based on the present knowledge and understanding of ageing process

many theories have already been put forward by the gerontologists.

### Theories of Ageing

Several theories have been advocated to account for ageing of cells, tissues and the individual as a whole. A group of theories postulates that ageing is caused by the accumulation of some harmful products of metabolism in cells and tissues of organisms. Thus, the adverse changes in the cellular environment cause ageing. Some biologists, on the other hand, believe that ageing in animals is dependent on an intrinsic genetic property of the cells of the body. To make a compromise between the above two theories a 'compromise theory' has been put forward. According to this, the process of biological ageing is an outcome of interaction between the genes—the bearers of hereditary characters—and the environment. For example, domestication increases the span of life in animals. Domestication results in the change of environment of the habitat in which the animals live. Another theory postulates that the animals with a high rate of metabolic activity age earlier and die sooner than those with a lower rate of metabolism.

According to another group of theories, collectively known as 'wear-and-tear theory' of ageing, the cells and tissues of animals are continuously subject to 'wear-and-tear' process due to intrinsic and extrinsic stress factors. Thus, animals gradually exhibit the signs and symptoms of ageing and eventually die.

'Somatic mutation theory' advocates that the gradual accumulation of deleterious gene mutations in the body cells results in functional incapacitation of tissues and organs as ageing symptoms.

Thymus gland produces cells which

combat the disease-causing bacteria and other microbes. According to the recently postulated 'immunity theory' of ageing, our body slowly loses the power of defence against the invasion of germs and pathogens. This process starts with the gradual atrophy and disappearance of the thymus gland during middle age. Further, with the loss of this gland body produces a greater number of abnormal and harmful cells which cause the increased rate of damage and destruction of tissues. According to still another theory the primary defects due to ageing appear at certain centres of the brain which control the functions of the endocrine glands. Such defects bring in hormonal malfunctions and imbalances in the body. For example, many mammals, including man, show signs and symptoms of ageing with the reduced production of sex hormones in the body.

Though each of the above theories attempted to explain with evidence the biology of ageing in one or other animal, none could explain the phenomenon in a way applicable to all animals. We may have to wait for some time more for a comprehensive theory of ageing. Such a theory can only be put forward with the accumulation of sufficient knowledge about the ageing processes in diverse types of species.

### DEATH

Death is a biological event which is due to permanent breakdown in body functioning, usually occurring due to lack of oxygen supply to tissues. The cells cease to perform normal function. The changes initiated in the cells block the restoration of normal function and lead to widespread cell breakdown and death.

Causes of death due to ageing are many but they fall under two principal categories. First, the weakening of the tissues



and vital organs such as heart, liver, kidneys, etc., results in physiological and metabolic disorders of irreversible nature. Such disorder leads to death due to the total breakdown of one or more vital processes of life. Sometimes, at a comparatively older age, sudden blockage in the circulation of blood to the heart and brain tissues causes instantaneous death. Secondly, due to ageing there is gradual breakdown in the immune system (a system which provides resistance to the body against the attack of disease-causing mi-

crobes). Thus, due to the loss of body resistance at old age individuals become vulnerably susceptible to infectious diseases. Many old age deaths are due to the attack of dreaded bacteria and other microbes.

Death is an inescapable event of life. It is an essential biological phenomenon for maintaining the balance of nature. It also justifies the 'perpetuation of self' and 'continuity of life' on earth as two meaningful characteristics of the living beings.

## SUMMARY

The process of development and differentiation in the body of a multicellular animal does not stop altogether even after the emergence of functional organs and systems. A young individual grows through a set pattern to attain the final shape, size and weight. Further, in the individual's body cells and tissues undergo wear-and-tear process. Some cells and tissues, and even the body parts of some animals are replaced and renewed. After attaining maturity, individuals gradually show signs and symptoms of growing old and die eventually.

The processes of growth, repair and regeneration and ageing may be described as the post-embryonic developmental events. At the cellular level, each of these processes involves one or more of the cellular processes of divisions, movement, elongation, differentiation, ageing, and replacement.

Differentiation and growth enable animals to become functional as individuals. Growth may be defined as increase in size and weight of the organism due to synthesis of protoplasmic and apoplasmatic substances. The growth of an individual takes place when anabolism dominates the overall metabolic process. When catabolism, i.e. the breakdown process, exceeds the synthetic activity within the living body, energy is obtained first by the consumption of stored food and then by the breakdown of proteins of the protoplasm. This is the process of degrowth.

The growth of the individual at the cellular level is dependent on cell multiplication and cell growth. But the relationship between the cell growth and the growth of the body as a whole is by no means a simple one. In relation to the growth and multiplication of cells constituting the body, the growth of animals falls under three categories. Increase in the volume of the body simply due to the growth of cells without any increase in the number of cells is called auxetic growth. The second category of growth, called multiplicative growth, is due to a rise in the number of cells constituting the body. (The average size of the cells remains the same or increases insignificantly.). Undifferentiated cells (as reserve cells) at certain locations of the body, in case of necessity, reinforce and replace the worn-out differentiated

cells by differentiating into the types of cells that they reinforce and replace. This type of growth constitutes the third category and is termed 'accretory growth'.

All higher animals grow at a specific rate and rhythm. The rate of growth can be depicted through a curve drawn by plotting the weights of the individual taken at different time intervals (in years). Such curves, with rare exceptions, will be 'S'-shaped (Sigmoid curves).

However, in human beings and higher animals different parts of the body grow at different rates and paces. The rate of growth in man from birth to 10-13 years of age is controlled by thymosin hormone. Towards the end of childhood the growth rate starts increasing due to the enhanced activity of thyroxine and somatotrophic hormones (STH). During puberty the rate of growth becomes fast and reaches the peak point due to the enhanced secretory activity of pituitary and other endocrine glands. At this phase of life, due to the action of sex hormones secondary sexual characters appear. With the completion of puberty, individuals become full grown and sex organs mature. Usually after 18 years the physical growth starts declining and almost ceases after 22-23 years of age.

Our body regularly loses cells from some parts such as skin, inner lining layer of the gut and mature red blood cells from blood. These cells are spontaneously replaced by the newly formed cells. Such spontaneous loss and regeneration of cells also occur in many other animals. Many animals can restore some body parts which are accidentally or spontaneously damaged. Regeneration of the lost part involves one or more cellular processes of migration, multiplication, differentiation and dedifferentiation. Thus, regeneration is a morphogenetic mechanism for repairing, replacing or reviving the damaged and severed body parts or reorganisation of the whole body from a body fragment (e.g. *Hydra*). *Hydra* and *Planaria* are endowed with the power of repetitive regeneration.

Animal regeneration falls under two broad categories—reparative and restorative. While the restorative regeneration is common in some invertebrate groups, the reparative one is quite common in both invertebrate and vertebrate groups.

Morphallaxis and epimorphosis are two principal mechanisms of regeneration in animals. Morphallaxis is the process in which from a small fragment the entire body of the animal is reconstituted by reorientation and reorganisation of the cells of the fragment. Epimorphosis, on the other hand, is the process in which through proliferation of the cells the lost body part is regenerated.

The life-span in diverse animal groups varies widely. The average life-span of a particular group excludes accidental deaths. After physical maturity characteristic changes take place in the body as it ages. These changes include a decline in the metabolic activity and a decrease in the power of replacing worn-out cells and repairing the damaged tissues, organs and organ-systems. One or more vital organs of the body ultimately stop functioning.

Ageing may be defined as deterioration in the structures and functions of cells, tissues and organs of an animal.

Various changes due to ageing are categorised into morphological and physiological, cellular and extracellular changes.

Morphological and physiological changes due to ageing are manifold. These changes affect structures and functions of skin, muscles, bones, etc. as also the vital organs such as heart, brain, kidney, etc.

Chromosomal aberrations in the cells of some organs, inactivation of cellular enzymes (e.g. aldolase in liver cells), formation of defective proteins, pigment accumulation and loss of power of cell division (in the brain and muscles) are conspicuous changes in the cells due to ageing.

Extracellular changes include structural and functional changes in collagen—the prime extracellular protein. Young collagens which are permeable, flexible and easily soluble transform with ageing into a less permeable, rigid and insoluble type. Such altered properties of collagens interfere with the normal function of surrounding cells. Such mechanical obstructions cause deterioration of cell functions and hasten the ageing process of the cells and tissues of the body, including those of the vital organs.

Biological process of ageing is not yet fully understood. Many questions pertaining to ageing remain unanswered. Gerontologists are still continuing their search to understand it fully.

Many theories have been propounded to account for the ageing of cells and the individual as a whole. Some experts hold the view that adverse changes in the cellular environment cause ageing. Others believe that ageing is dependent on the intrinsic genetic property of cells of the body. A 'compromise theory' advocates that ageing is an outcome of interaction between the genes present in the body of an individual and the environment in which the individual lives. Still another theory postulates that animals with a high rate of metabolic activity age and die earlier than those with a lower rate of metabolism.

'The wear-and-tear' theory of ageing lays emphasis on intrinsic and extrinsic stress factors on the continuous 'wear-and-tear' process of the cells and tissues of animals. 'Somatic mutation theory' holds that gradual accumulation of deleterious gene mutations in the body cells results in functional incapacitation of tissues and organs as ageing symptoms. According to the recently propounded 'immunity theory' of ageing, gradual atrophy and disappearance of thymus gland jeopardises the defence mechanism of the body for combating invasion of germs and pathogens. With the abolition of this gland the body produces a greater number of harmful abnormal cells which cause the increased rate of damage and destruction of tissues. Still another theory holds that the primary defects due to ageing develop at certain centres of the brain which control the function of the endocrine glands. Such defects result in hormonal malfunctions and imbalances in the body which initiate changes characterising ageing.

Death is a biological event which results in irreversible breakdown of body functions and usually occurs due to lack of oxygen supply to tissues. Changes initiate in cells that are irreparable leading to widespread cell breakdown and death.

The causes of old age death fall under two principal categories. First, the irreversible physiological and metabolic disorders initiate in the body due to the weakening of tissues and vital organs. Such disorders lead to death because of the total breakdown of one or more vital processes of life. Secondly, a gradual incapacitation of the immune system of the body takes place with age. Individuals are vulnerably susceptible to infectious diseases during old age.

## QUESTIONS

1. Define the term 'growth'.
2. What are the three principal types of growth? Explain each of them with an example.
3. Distinguish between
  - (a) growth and degrowth
  - (b) protoplasmic and apoplasmatic substances
  - (c) auxetic growth and multiplicative growth
4. Write notes on:
  - (a) growth rate
  - (b) growth curve
  - (c) cell growth
  - (d) accretionary growth
5. Describe briefly the characteristics of growth of human body parts. What do you know about the hormonal control of human growth?
6. Define the term 'regeneration'.
7. What are the two main categories of animal regeneration? Explain them with examples.
8. In what way is regeneration similar to embryonic development?
9. Distinguish between morphallaxis and epimorphosis.
10. Compare the mechanism of regeneration of *Hydra* from its body fragment with the regeneration of limb in salamander.
11. What are the characteristic cellular and extracellular changes occurring in our body due to ageing?
12. Write a note on the theories of ageing.

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